Modeling of “Mist Target” – the Ideal Target for LPP Source

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People contributed to the presentation

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KIAM: V. Novikov, A. Grushin,
A. Solomyannaya

Outline

- Why droplet-like target is not good one for HVM LPP source
- Model characteristics
- Comparison of calculated data with experimental one on plane Sn target
- Example of distributed target: spherical layer, movie
- Benefits of distributed target
- Conclusion

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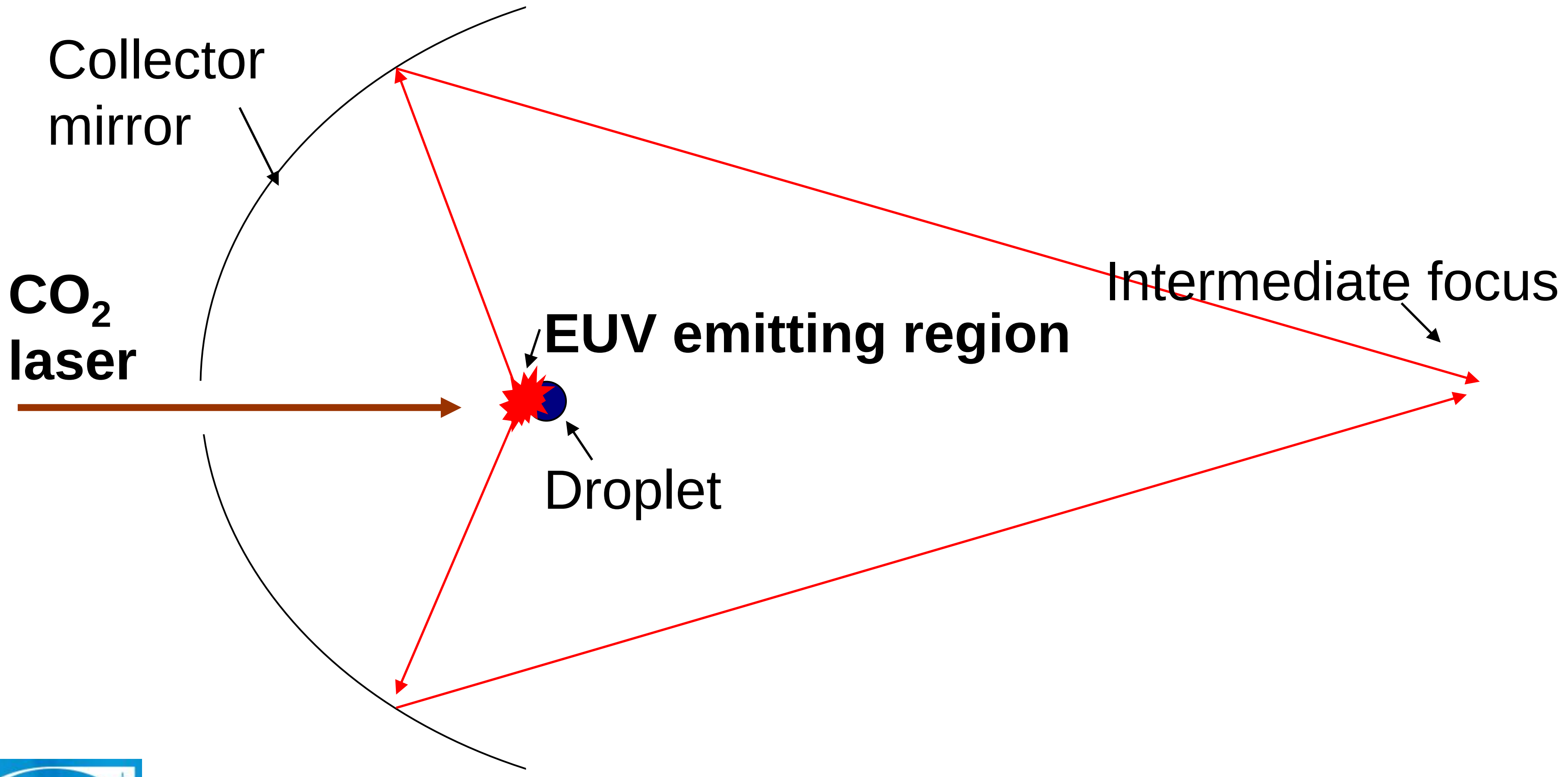
LPP EUV source approach



Moving to EUV LPP source for High Volume Manufacturing (HVM)

1. It is difficult to increase laser frequency over 50-100 kHz (it need high velocity of droplet for example)
2. So increasing laser pulse energy looking like the simplest way to EUV LPP source for HVM

Lets choose some reasonable values of laser parameter:

- Gauss-like temporal and space profile
- Laser spot diameter 200 um (1/e^2)
- Duration 120 ns (FWHH)
- Laser pulse energy 0.1 - 0.75 J

And see what consequences may follow from it (using RZLINE code)

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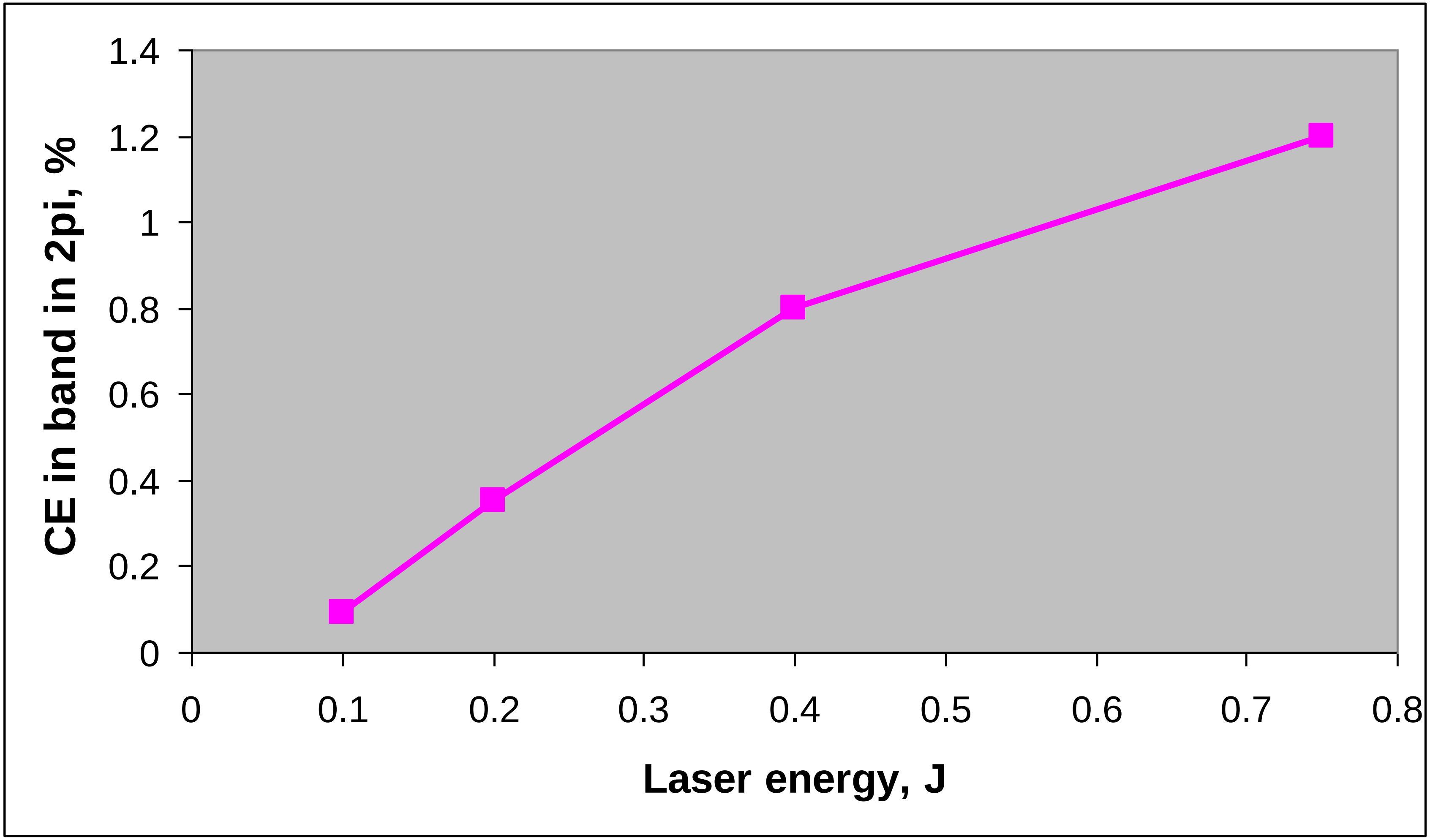
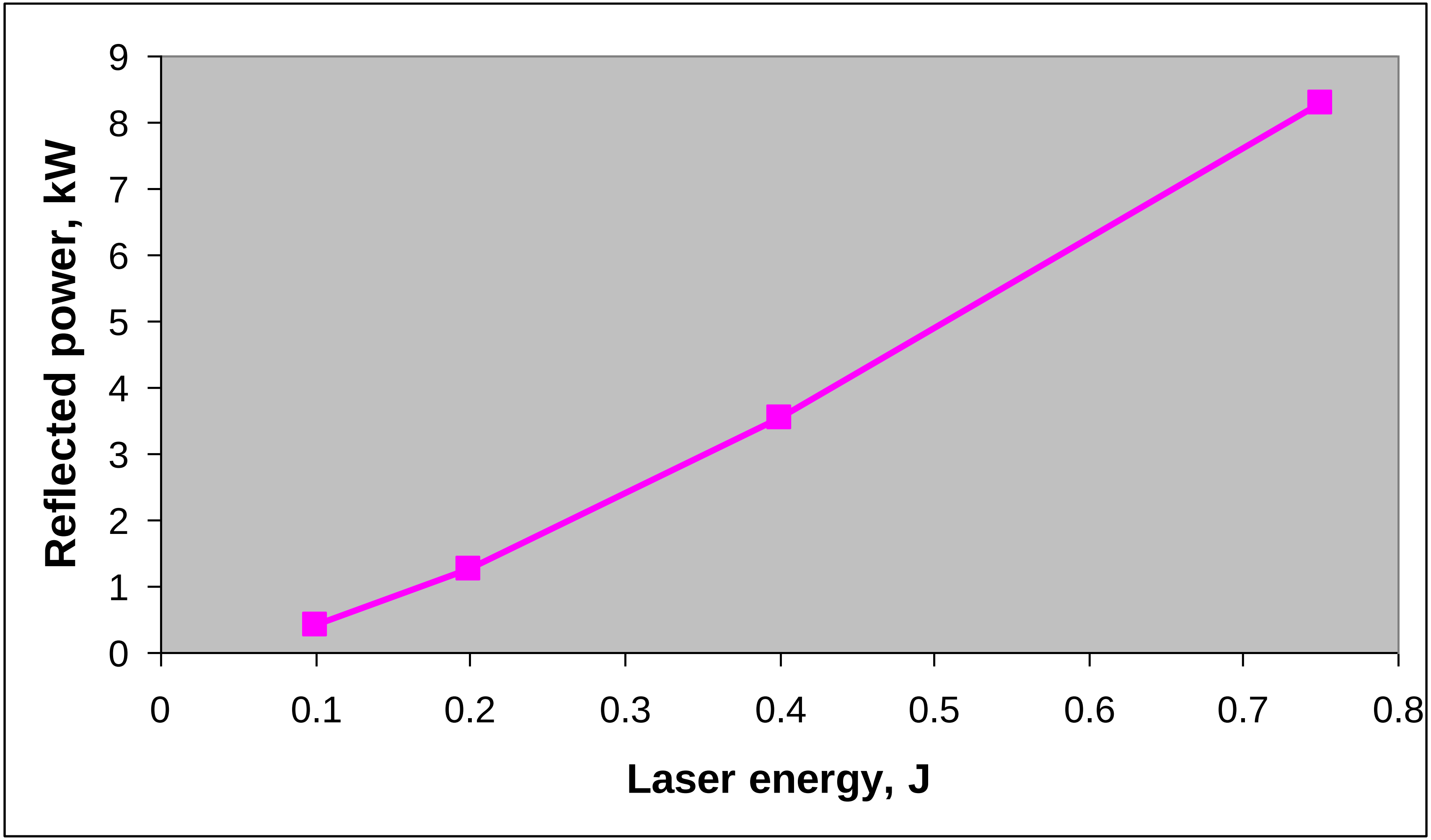
Conversion efficiency, 30 um droplet



CE is increasing with laser energy due to larger diameter of plasma clouds (faster evaporation of droplet). It increase coupling of laser beam and droplet.

Reflected power for 30 um droplet



Laser frequency is 50 kHz; at 0.75 J reflection is larger then 20% of incident laser power. It need strong spectral filter which decrease real CE essentially.

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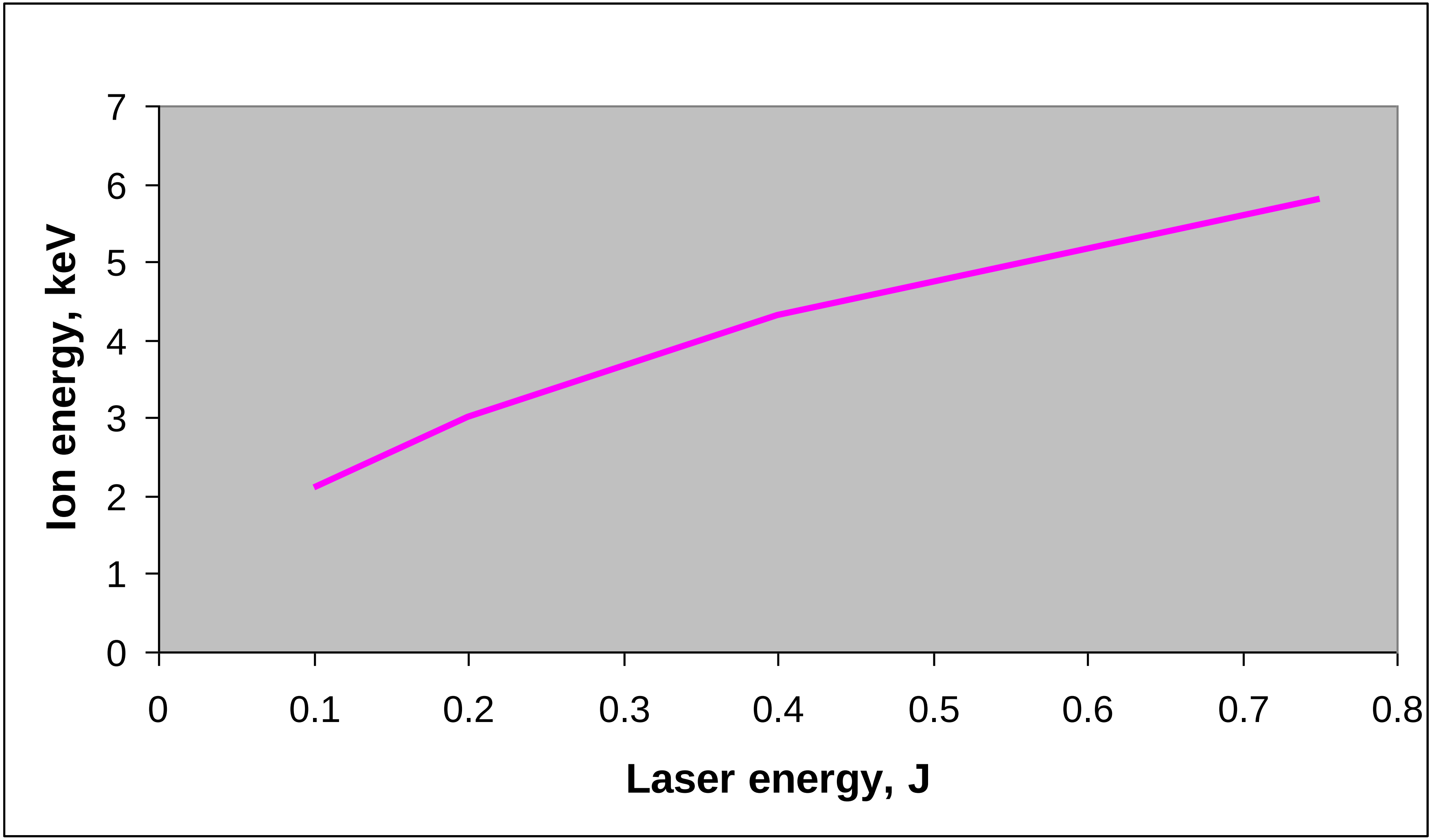
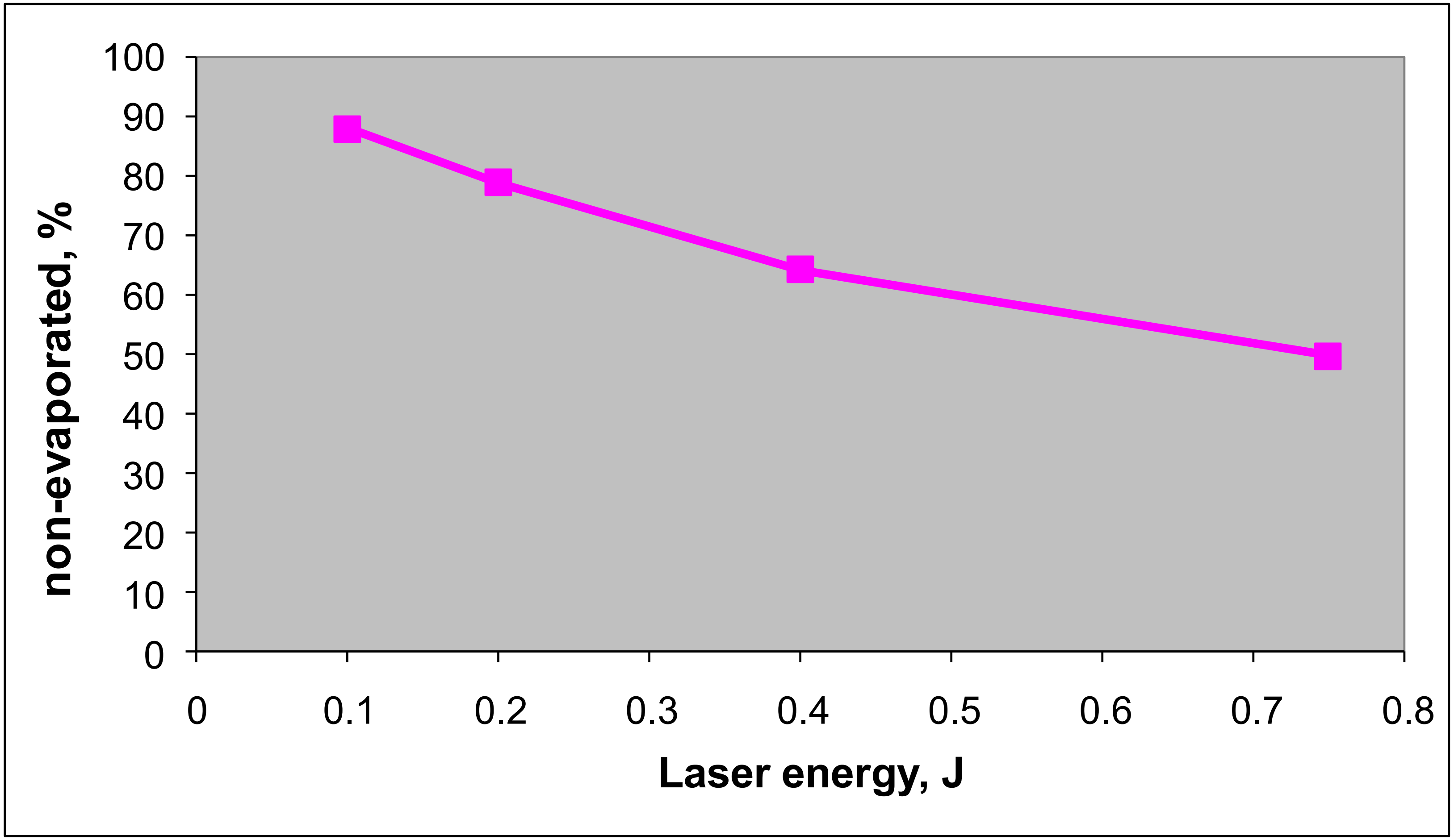
Ion energy for 30 um droplet



Fast increase of ion energy with laser energy may lead to problem with condenser mirror etching

Not evaporated part of droplet



1. Non-evaporated part of droplet may be a source of fast fragments after CO2 pulse
2. Neutral component is about 3.5% of droplet mass at 0.4 J

Several words about the RZLINE code

- First of all it was made partially by physicists, and it means that choose of needed processes as well as true representation of them in the code was in focus
- Nice stability of the code: you may put 20 variants on 4 processor PC and for sure have the resulting data next day.
- Detailed data for any variants are saved separately under names you like. Main results may be gathered automatically to one Excel-like document.

Radiative transfer

1. We used code THERMOS-BEELINE which makes possible self-consistent calculation of level kinetics and radiation transport including overlapped spectral lines with arbitrary optical thickness and realistic line profiles;

2. Verified atomic database for Li, Sn, Gd, Tb and their mixtures.

3. Details are in article in “High Energy Density Physics”, V.3, 2007, p. 198-203

Other RZLINE code characteristics

- 2D(r,z) Hydro-Dynamic and Radiative Transfer
- Diffusion-like radiation transfer in 100-5000 groups with well represented in-band EUV region
- Ion spectra resolved in energy and polar angle
- Simplified description of reflected and absorbed CO2 laser energy based on true solution of Maxwell equation in plane MLM
- EUV source size, detailed spectra and anisotropy of EUV radiation due to method of long characteristics
- Any distribution of small liquid Sn fragments (droplets) in space and size; evaporation and motion of them during laser pulse

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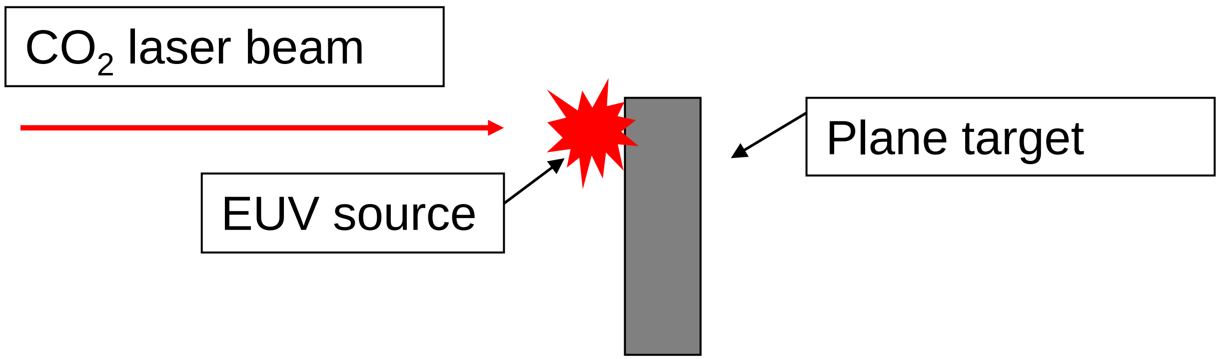
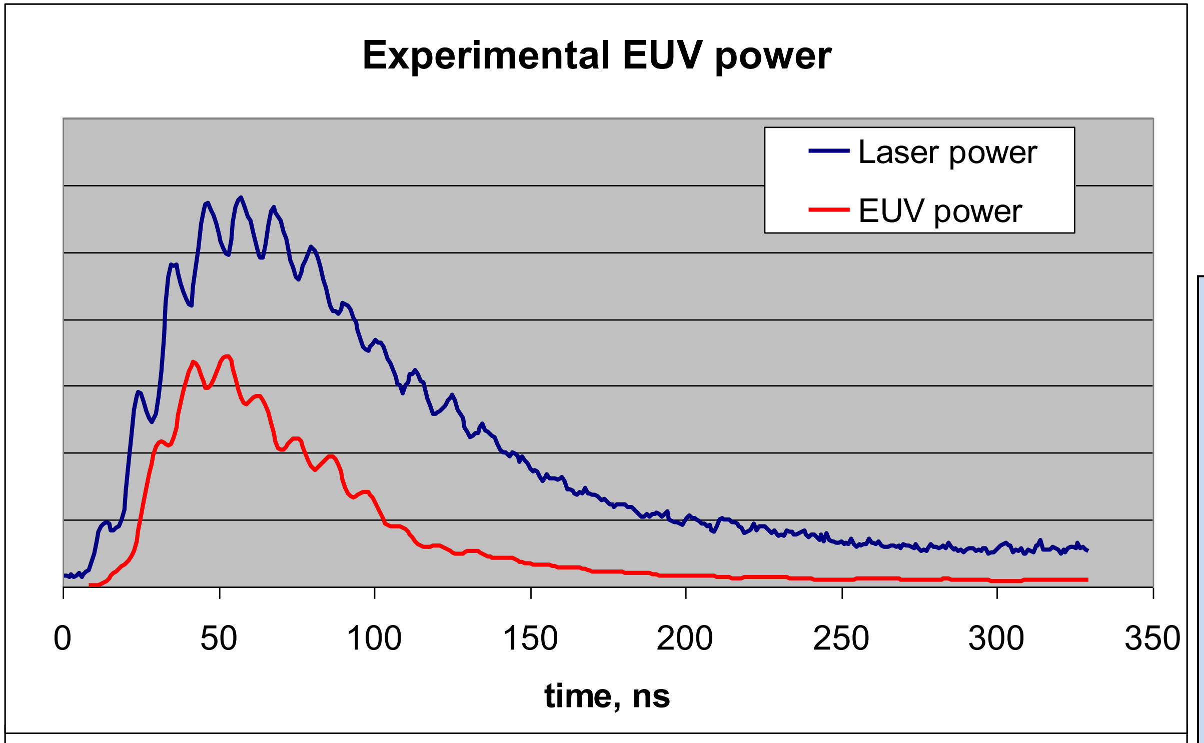
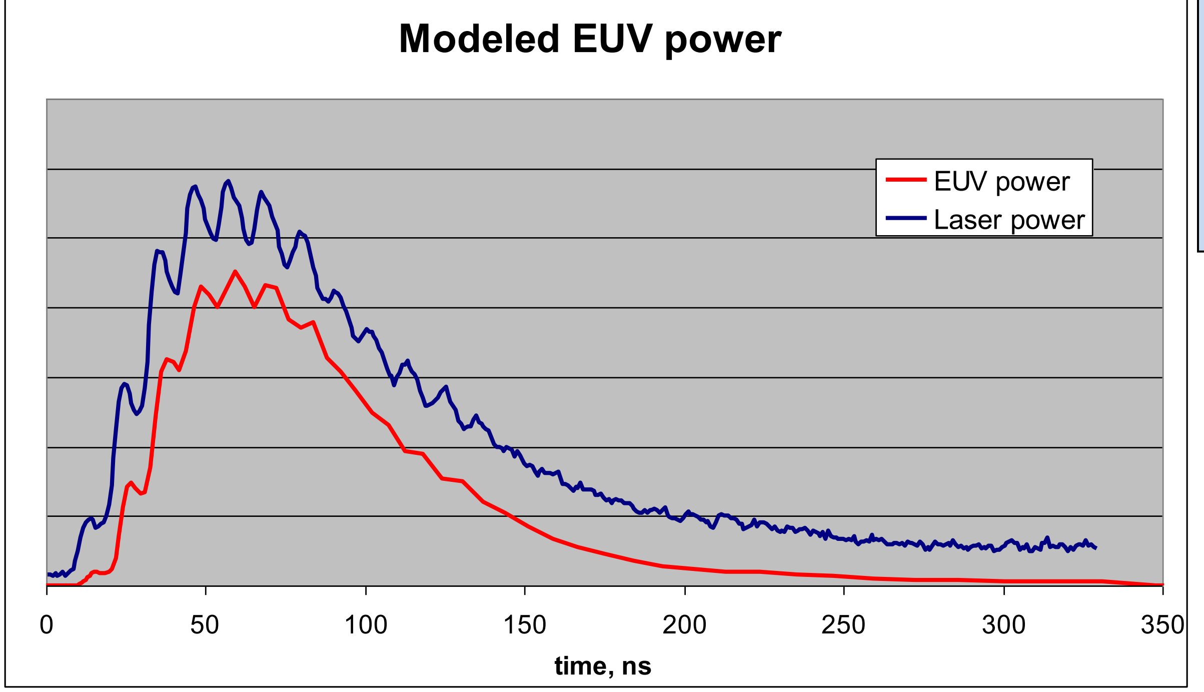
Comparison of calculated data with experimental one produced in ISAN on plane Sn target

Description of the experiment

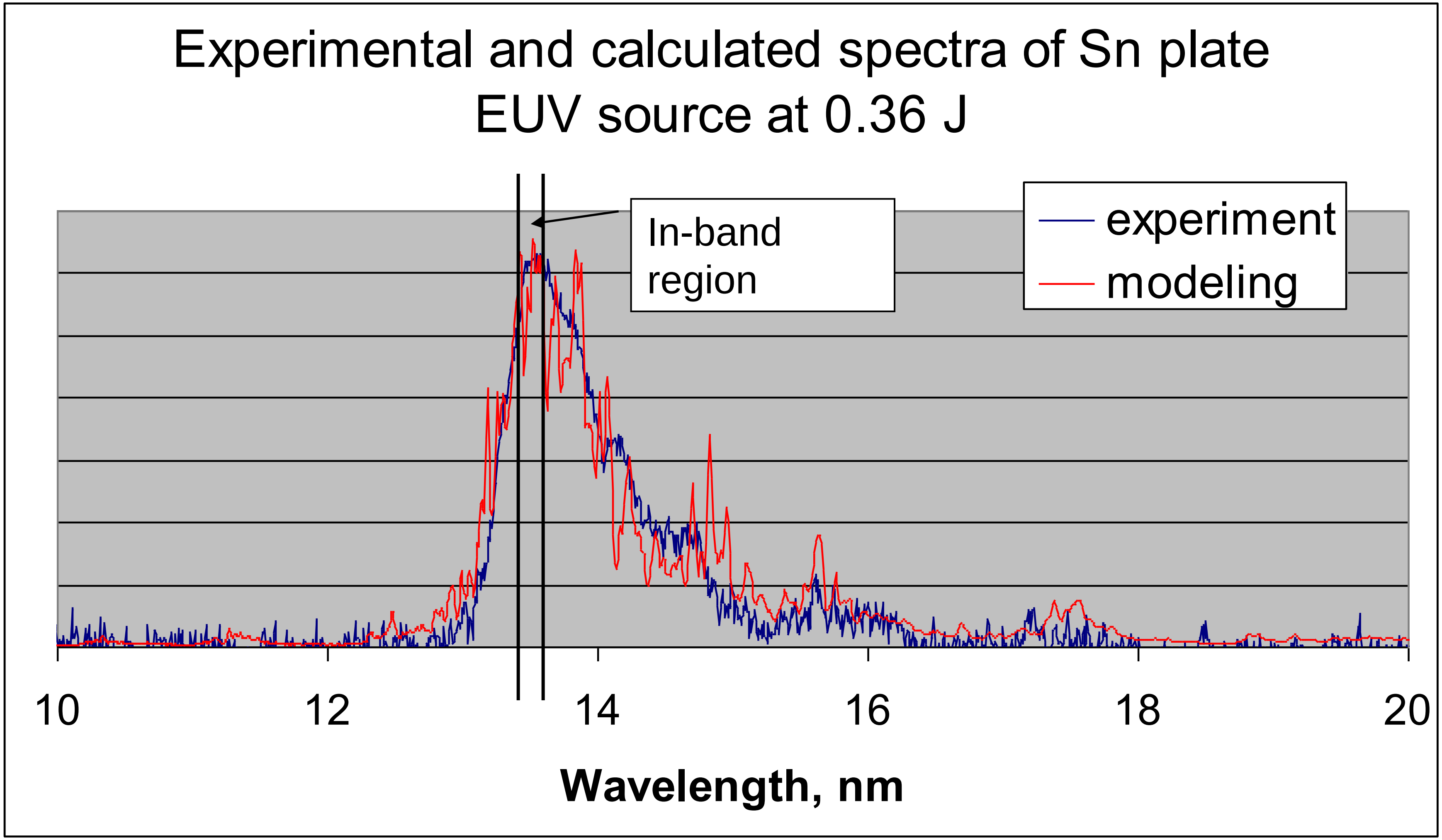


- CO_2 laser beam energy was 0.36 J
- Radial distribution of laser power density close to Gaussian with size 300 μm ($1/e^2$)
- Temporal dependence will be shown later
- Experimental data on EUV source spectra, EUV power, EUV isotropy, EUV source size were used for comparison with calculated results





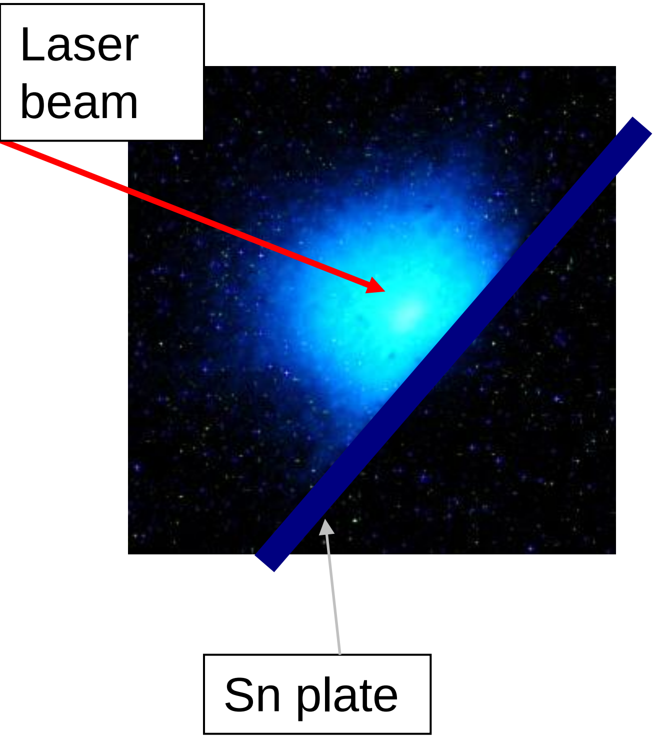
1. Calculated time dependence of in-band EUV power repeat qualitatively its experimental behavior
2. Experimentally seen long tail of EUV radiation was modeled as well
3. In band EUV repeats laser pulse waveform with delay ~ 3-5 ns



1. Experimental and calculated spectra are coincides rather well
2. Other spectral regions were calculated too, though without detailed grid. Only negligible part of energy was emitted there ~< 1%
3. Smoothed character of experimental spectra near in-band region is

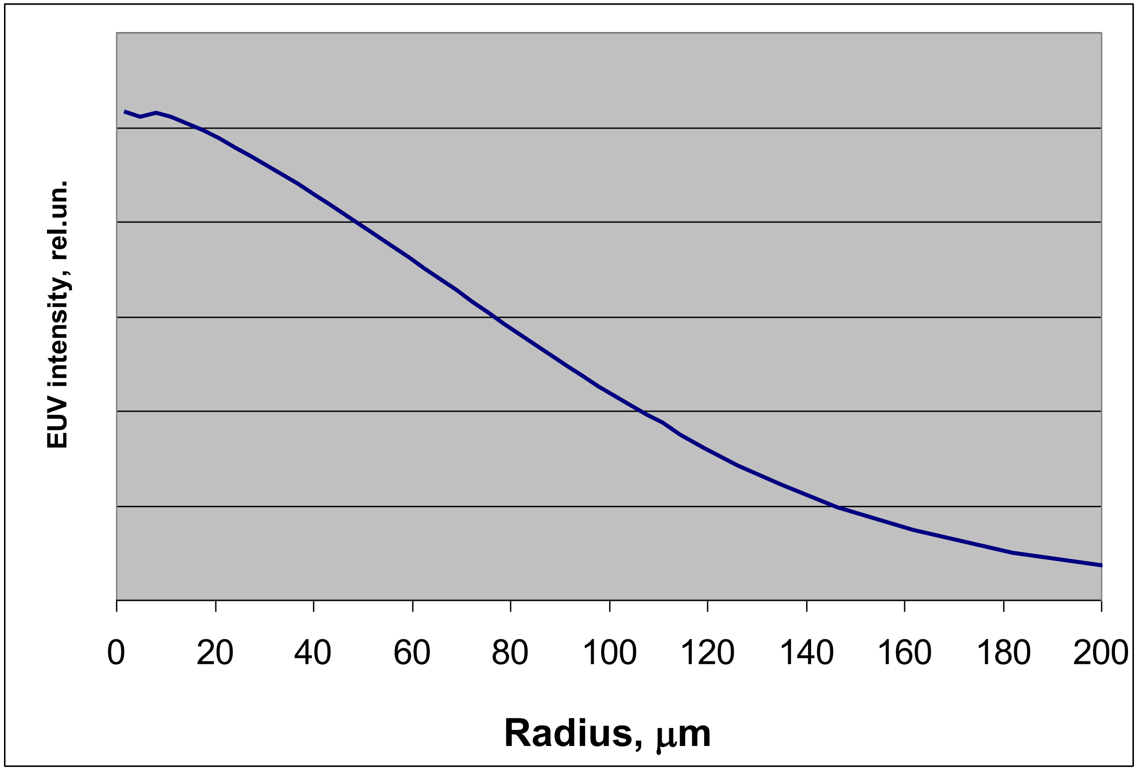
EUV source size

Experiment

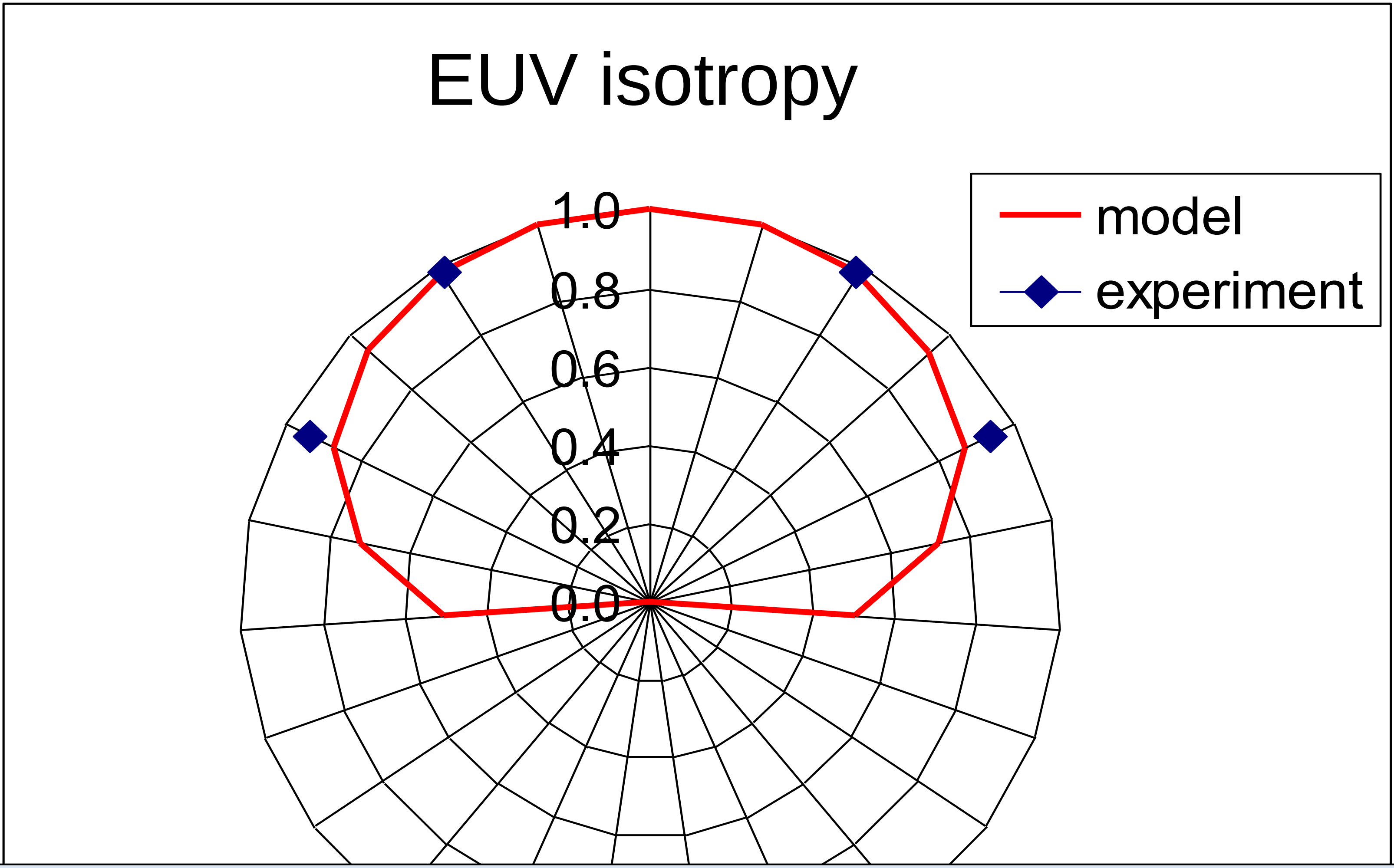


Pinhole image gives EUV source size about 300 μm ($1/e^2$)

Modeling



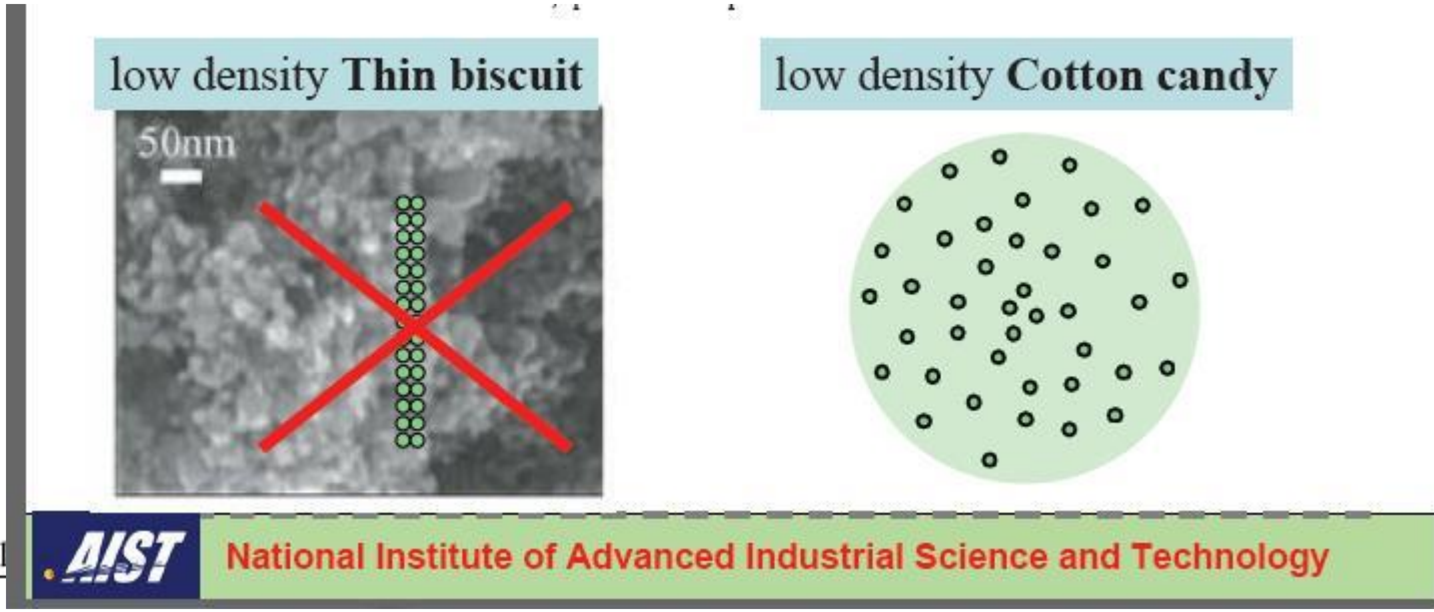
1. EUV source size, D = 2*R is about 350 μm ($1/e^2$), which is close to experimental one
2. EUV source size is defined mainly by laser focus spot size
3. It is slightly increase with laser energy



1. Vertical direction, polar angle $\theta = 0$, corresponds to direction to laser source
2. Isotropy of our plate EUV source is high in 5 steradian of collector mirror
3. Experimental EUV isotropy is slightly higher than calculated one

May be first references on distributed targets for EUV

PRL 94, 01



week ending
JANUARY 2005

Ultimate Efficiency of Extreme Ultraviolet Radiation from a Laser-Produced Plasma

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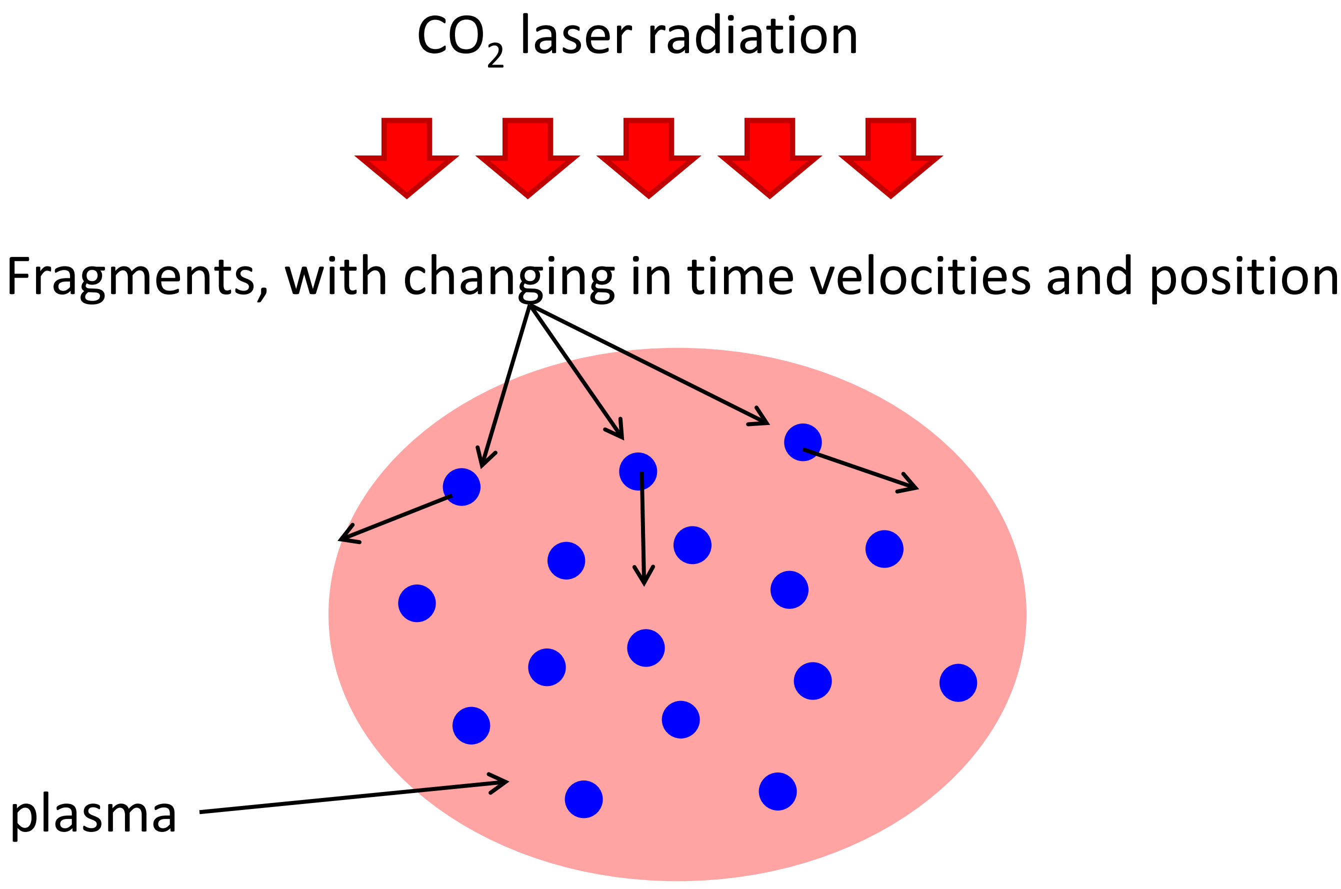
(Received 9 May 2004; published 7 January 2005)

Distributed(mist) target in RZLINE

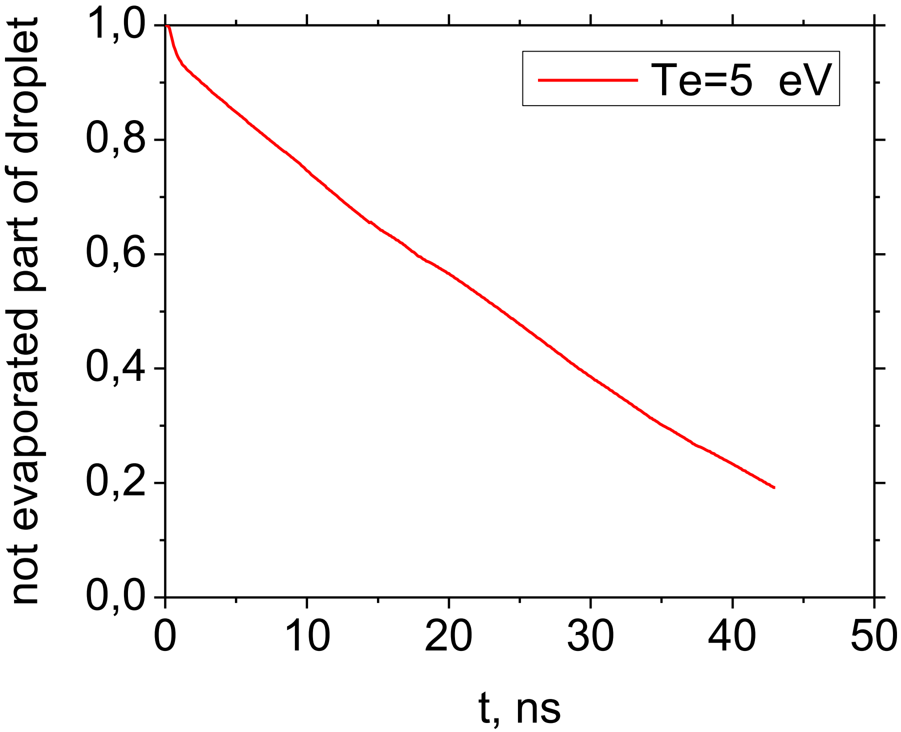


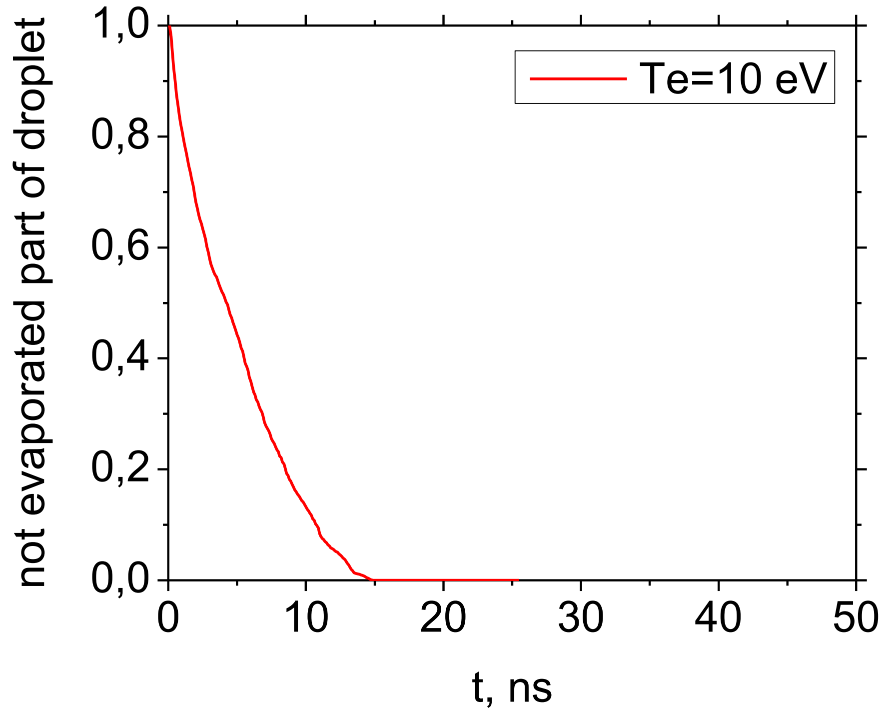
1. Rate of evaporation of fragment (droplet) of some size is a function of plasma parameters around fragments: temperature, velocity, pressure as well as laser intensity near it
2. Fragments are moving during laser pulse under action of plasma

Fragment evaporation rate modeling

Modeling was done by standard RZLINE code. Fragment in the form of droplet was placed a region (30 um * 30 um). Plasma with given parameters is flowing into this region leading to evaporation of fragment. Really size of the region is an additional parameter, influence of which on results is not checked jet.

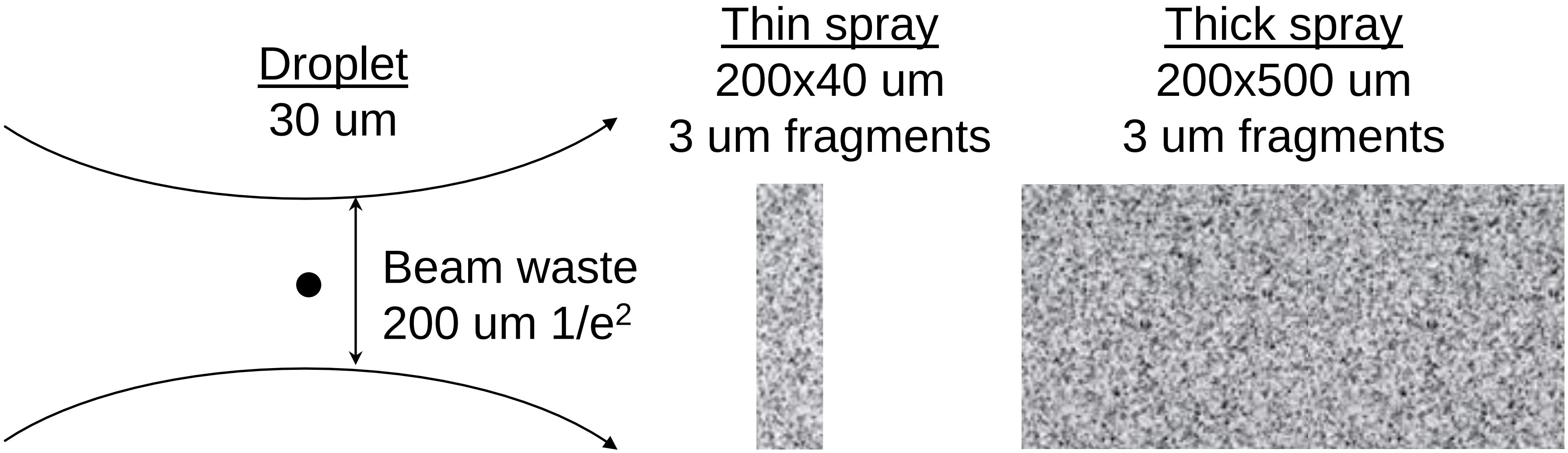
Example of modeling: d=3 μm, p=300 bar, u=3 km/s





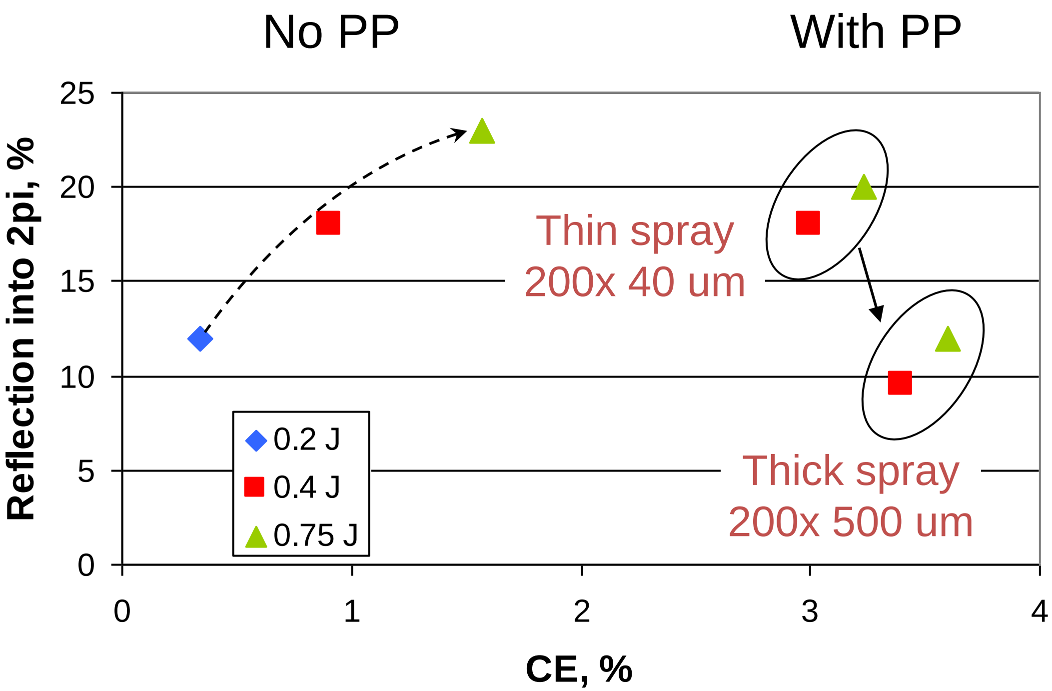
Only one parameter was used from these type of modeling – characteristic time of full evaporation of fragment.

Other possible geometry of distributed target



- Total mass of all targets is equal to that of initial droplet of 30 um

Expected scaling of 10.6 um reflection from LPP target



Assumptions:

- Droplet volume 30 um
- Laser spot: 200 um 1/e^2
- Pulse duration: gauss 100 ns

• Thick spray target with dimensions ~200x500 um is expected to have ~1.5-2x lower IR reflectance as compared to that of a thin target

•Though problem of optimal droplet splitting in pre-pulse stage arises (as in size as in space distribution).

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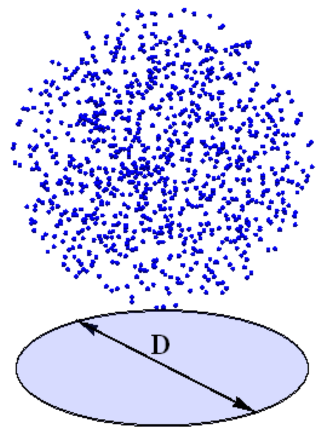
CE vs mist expansion

Mist target parameters:

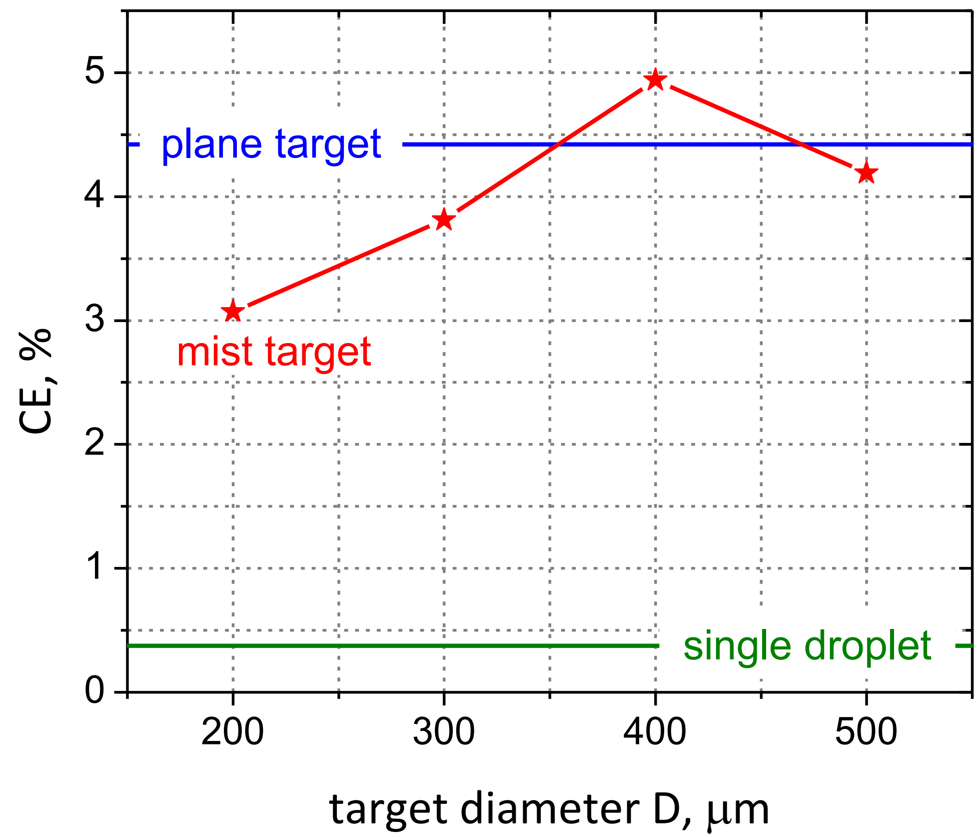
- expanded sphere
- uniformly spread fragments
- fragment size 1 μm



Laser pulse parameters:

- Gaussian time shape
  - 15ns FWHM
- Gaussian intensity profile in focal spot
  - 300 μm diameter on $1/e^2$ intensity level
- pulse energy – 0.1J
  - $\sim 10^{10}$ W/cm^2 power density

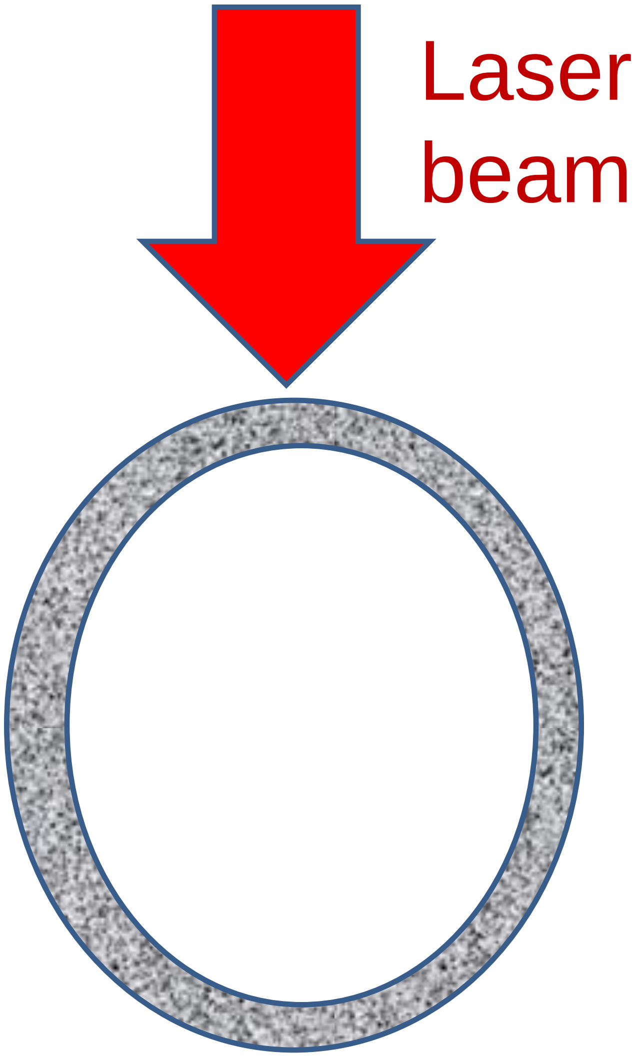
RZLINE calculations: in-band CE in 2π



Calculated with account for EUV angular anisotropy

Some example of plasma dynamics in distributed target

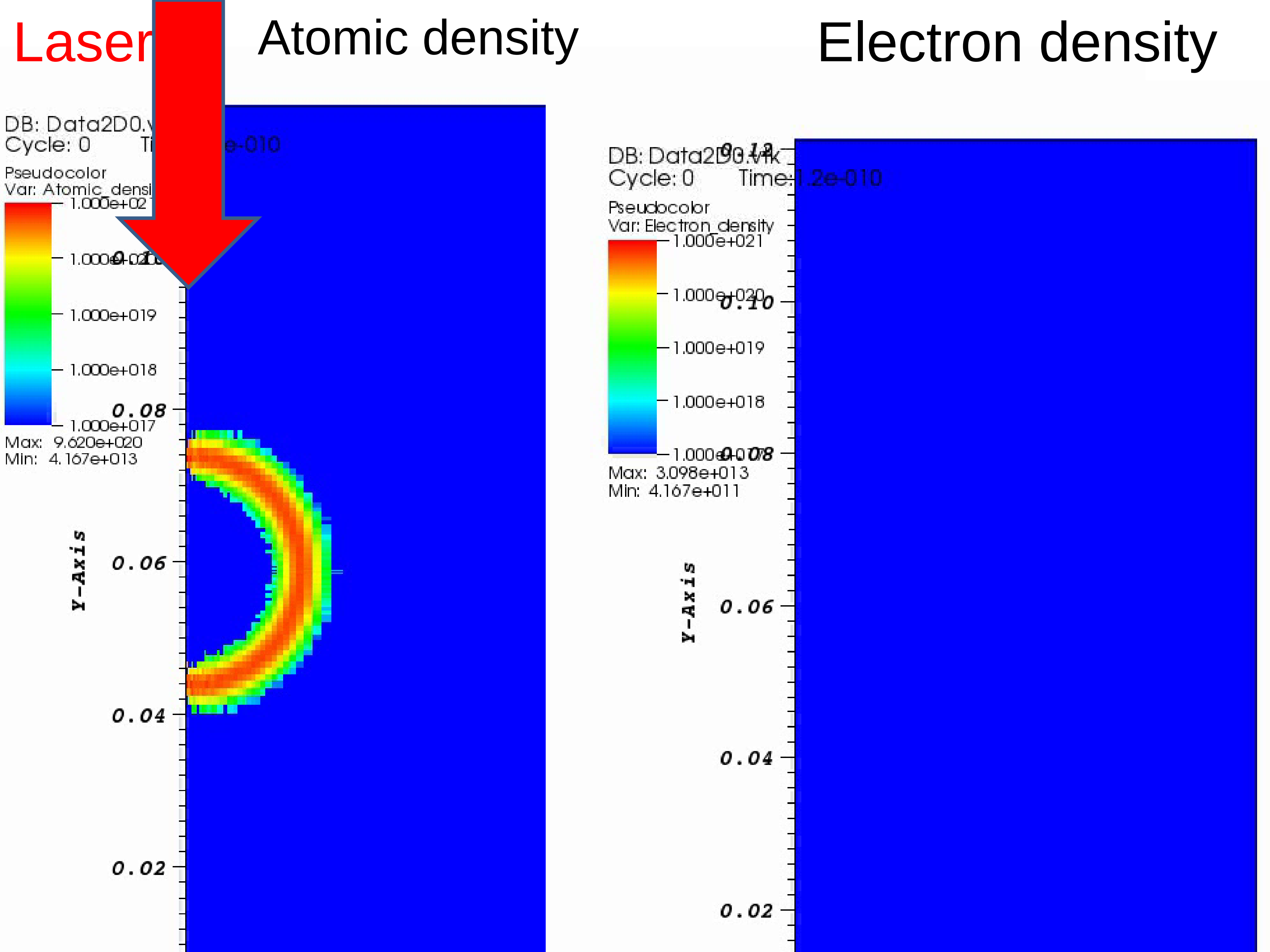
- 30 um layer of 300 um diameter sphere is filled with 1 um fragments with full mass equal to 60 um droplet
- Laser energy is 0.5 J
- Laser duration is 100 ns (FWHH), gauss
- Laser whist is 200 um (1/e^2), gauss



Laser

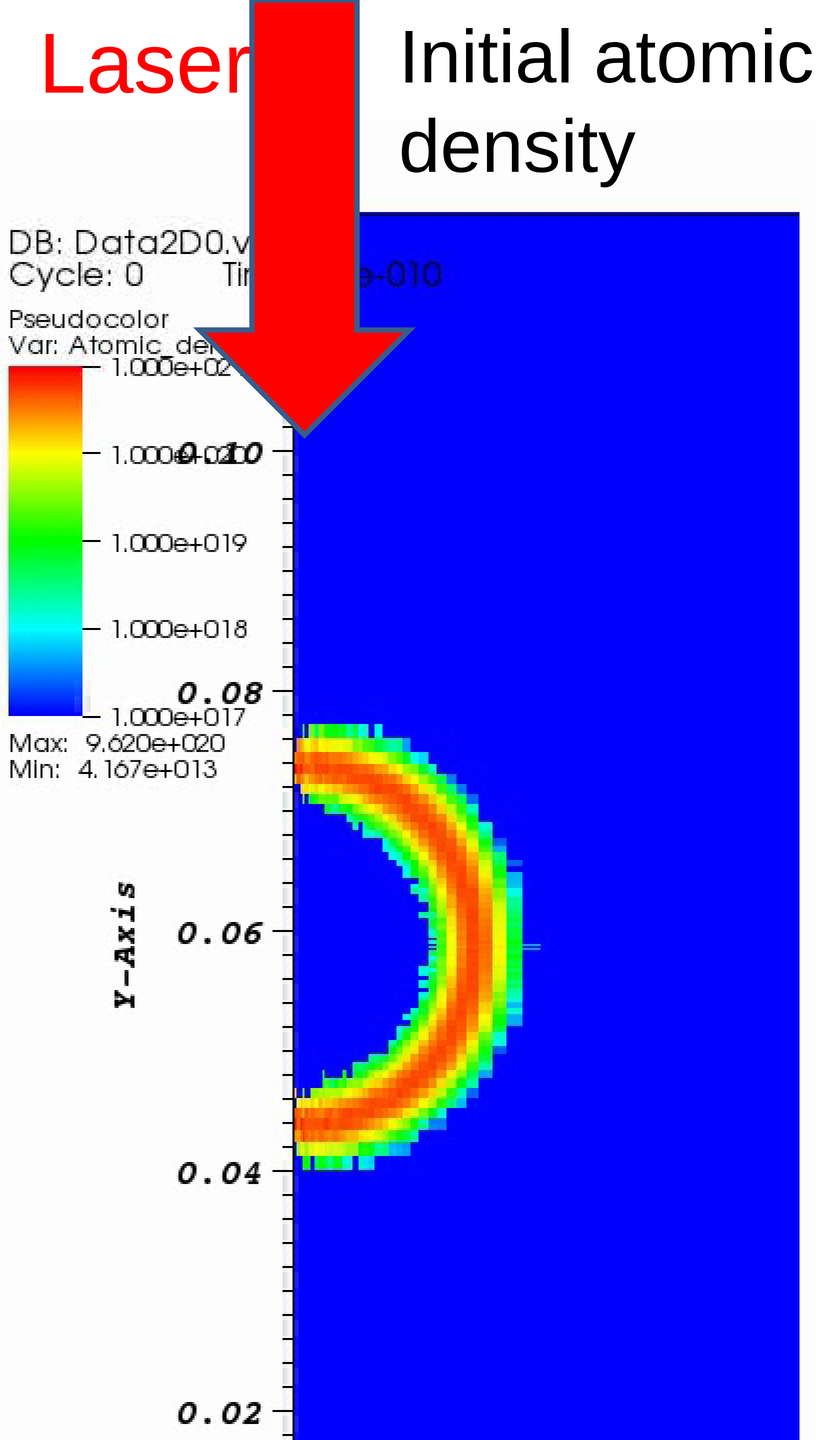
Atomic density

Electron density

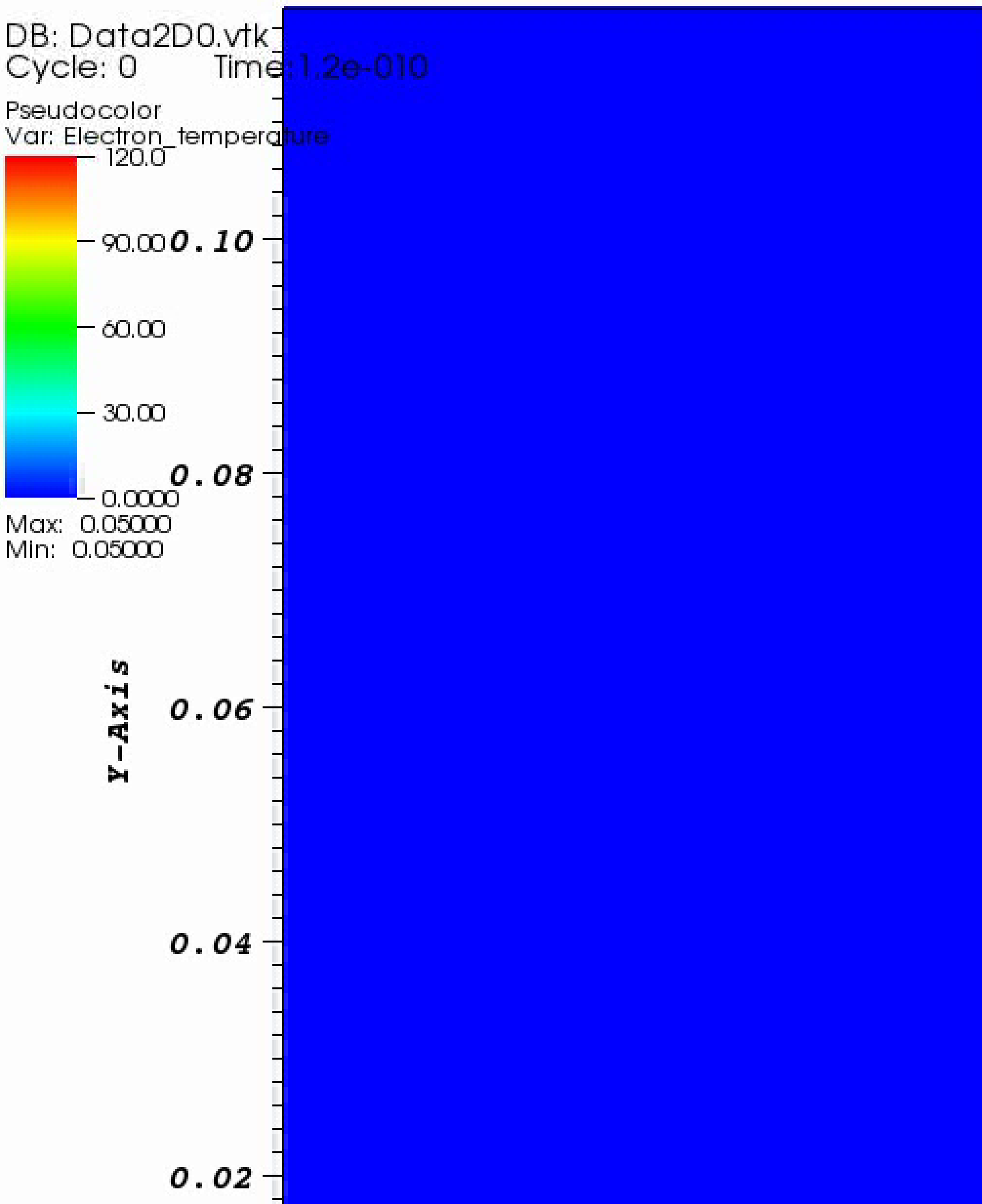


Laser

Initial atomic density

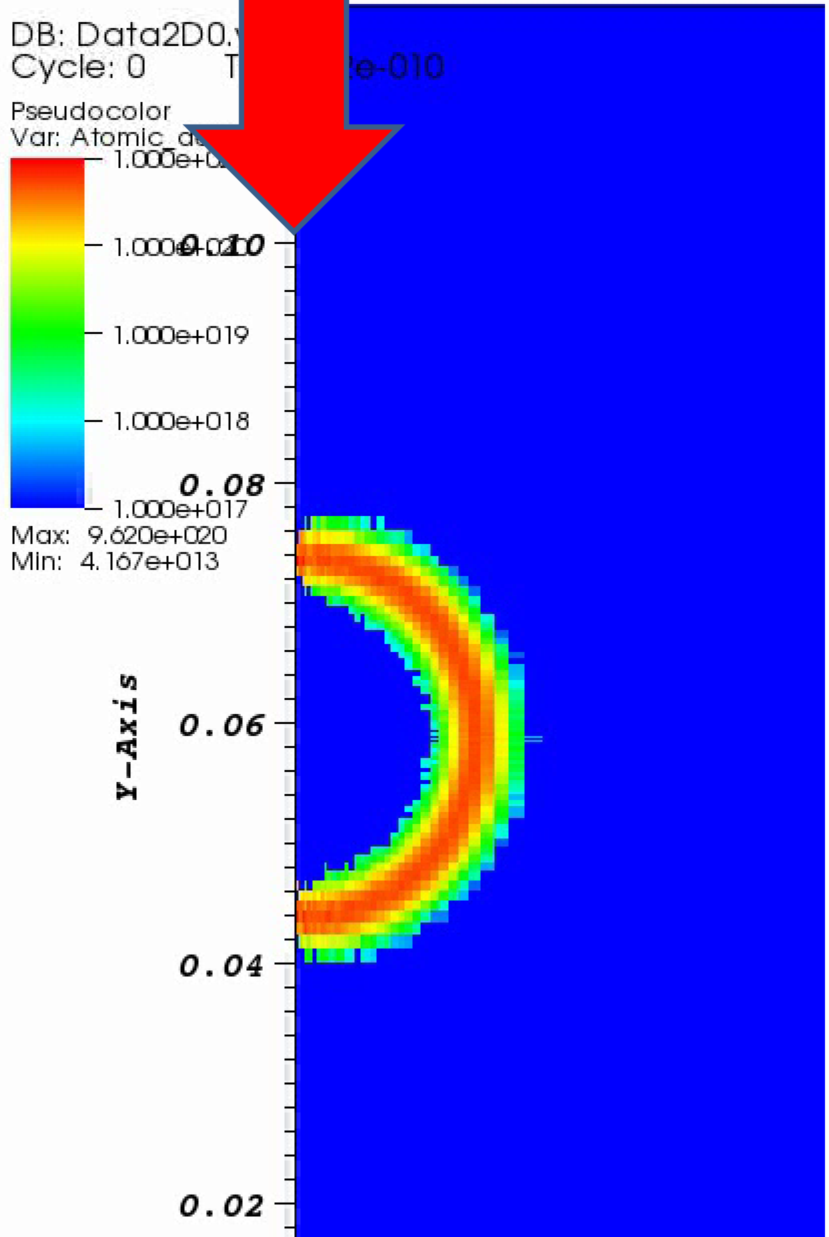


Electron temperature

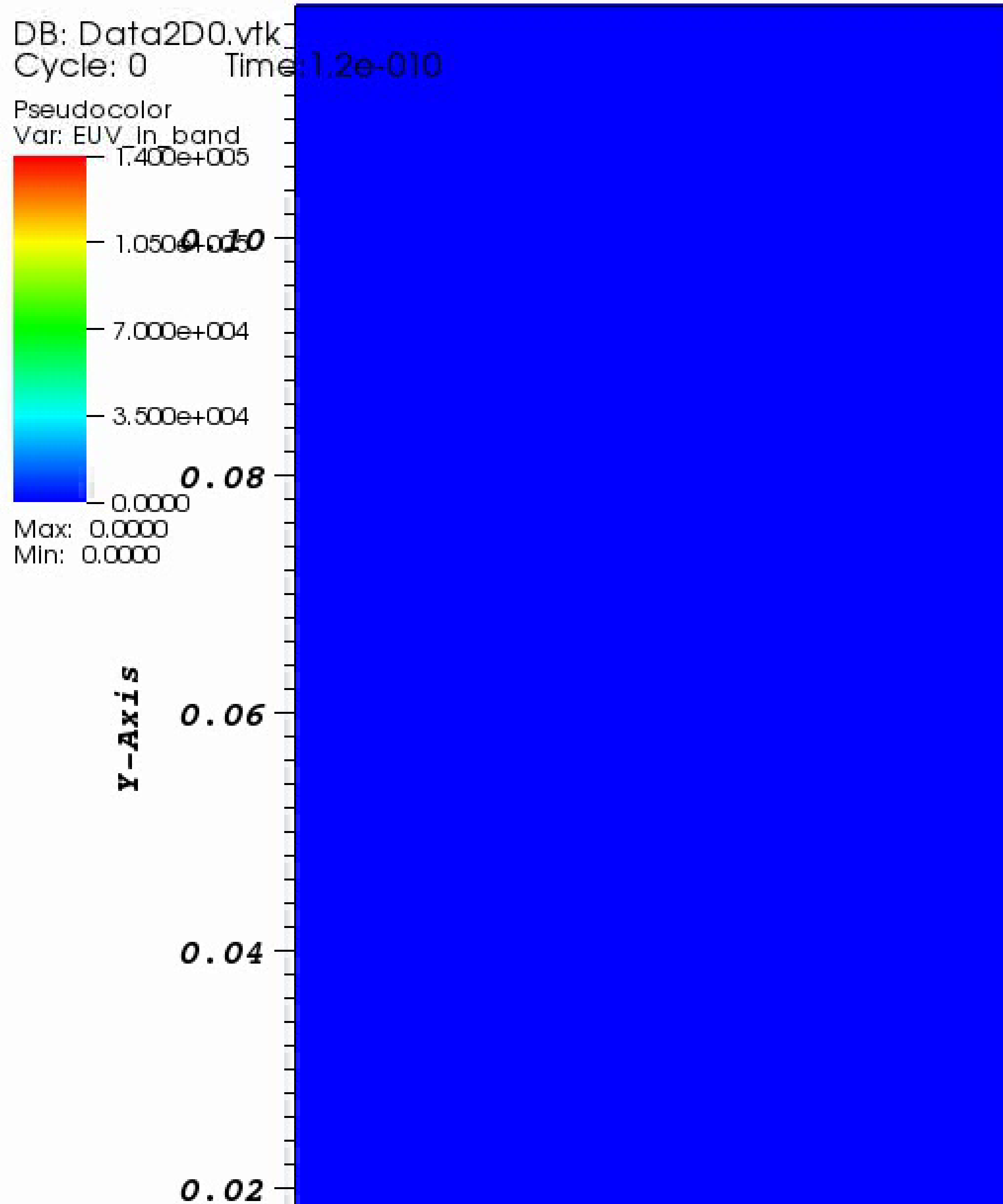


Laser

Initial atomic density

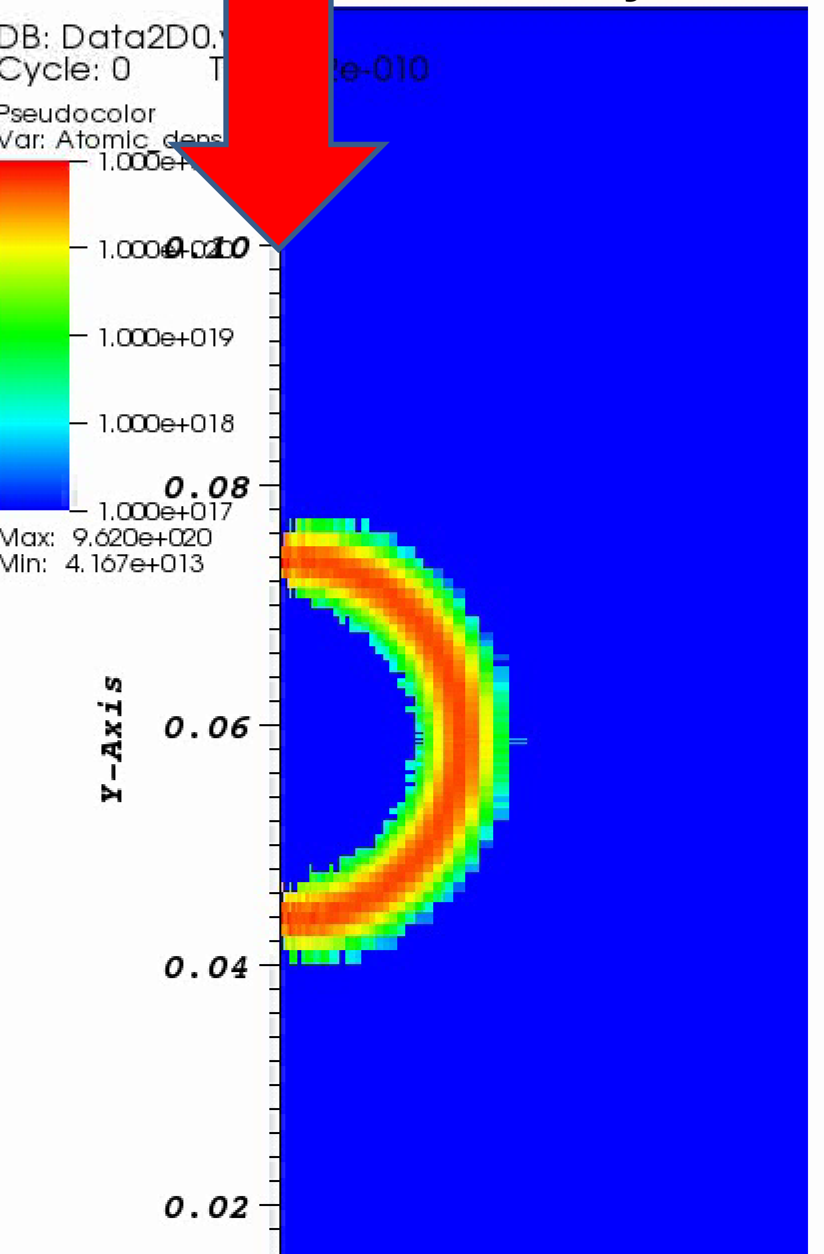


EUV intensity

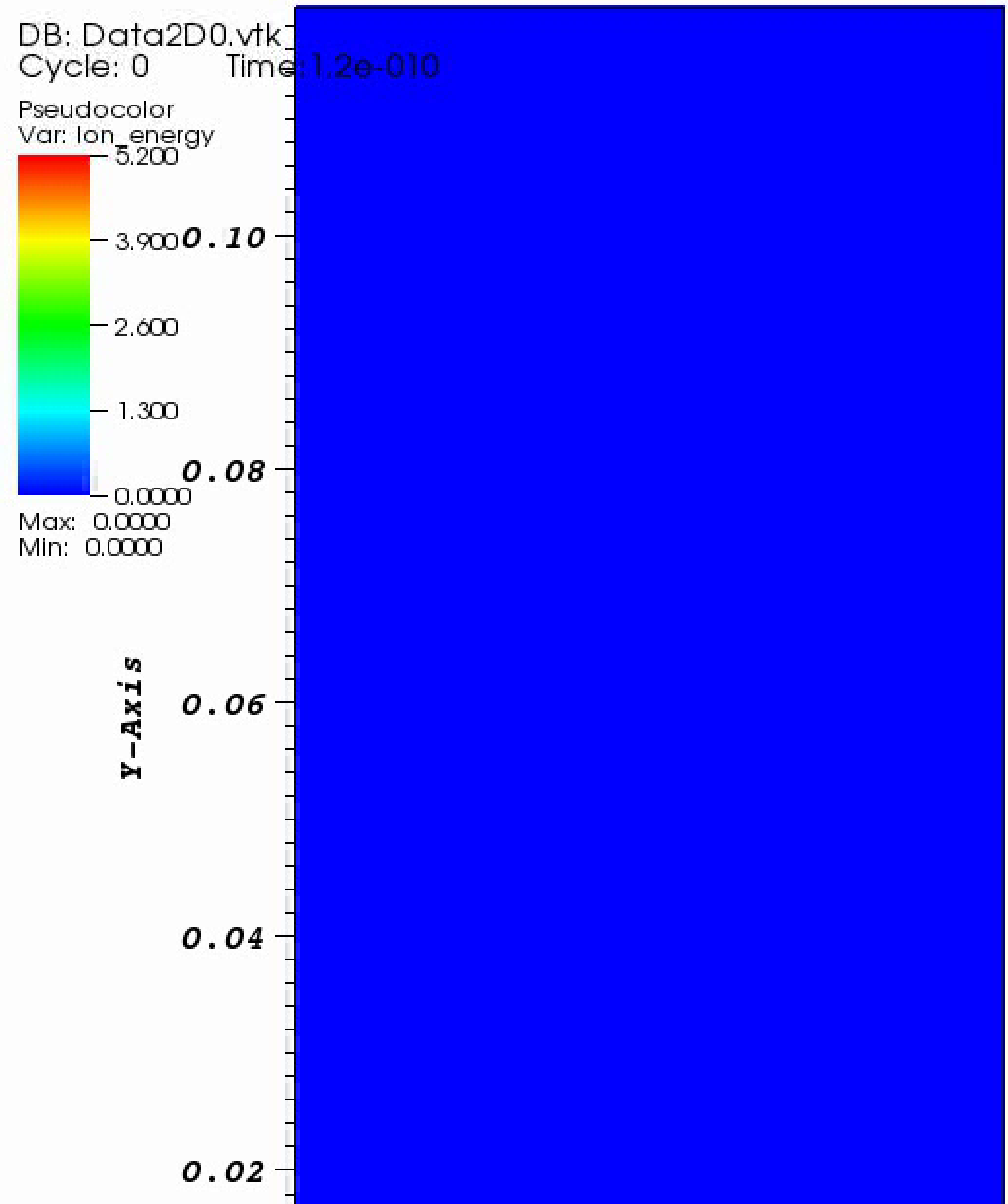


Laser

Initial atomic density



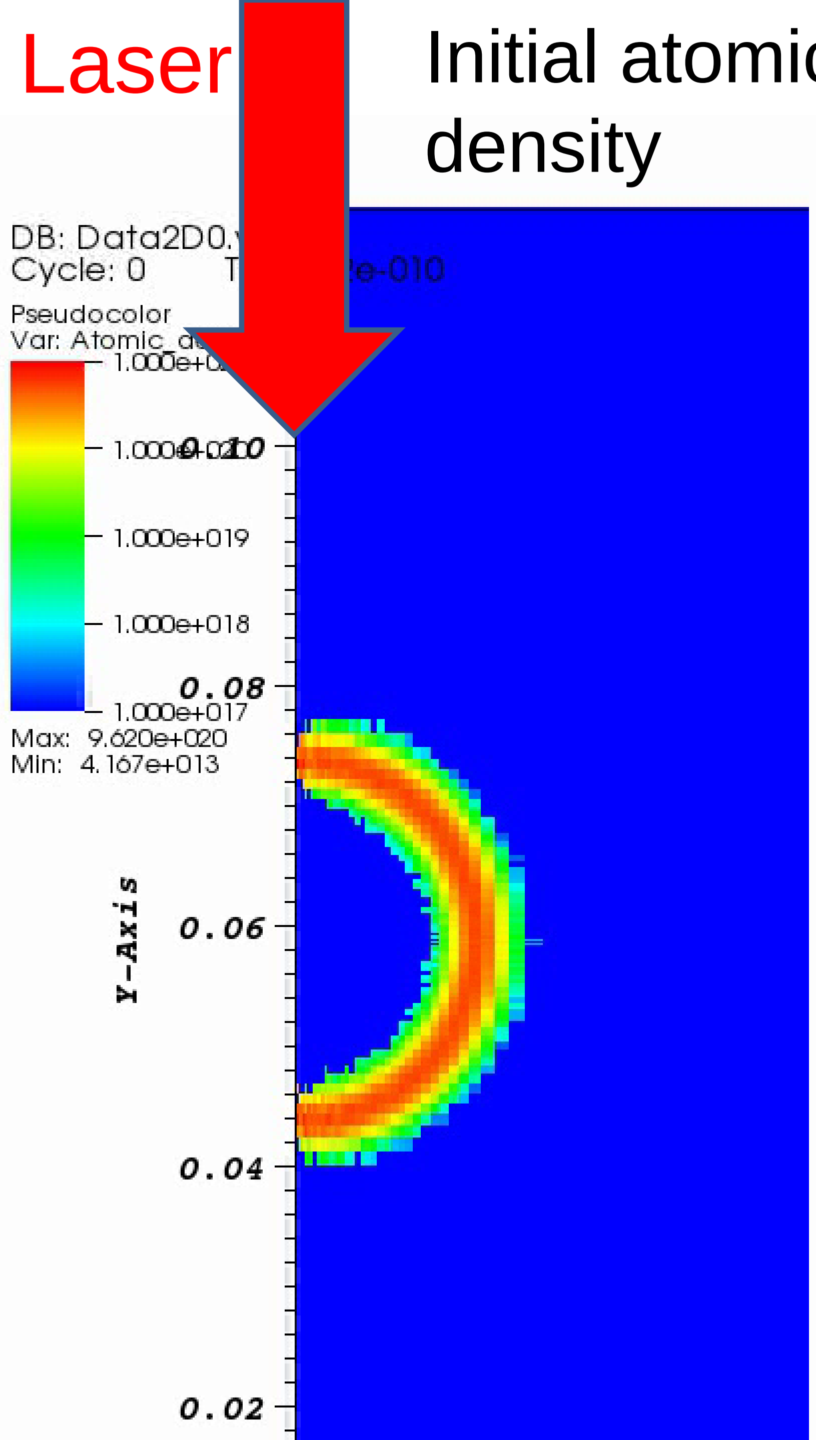
Ion energy

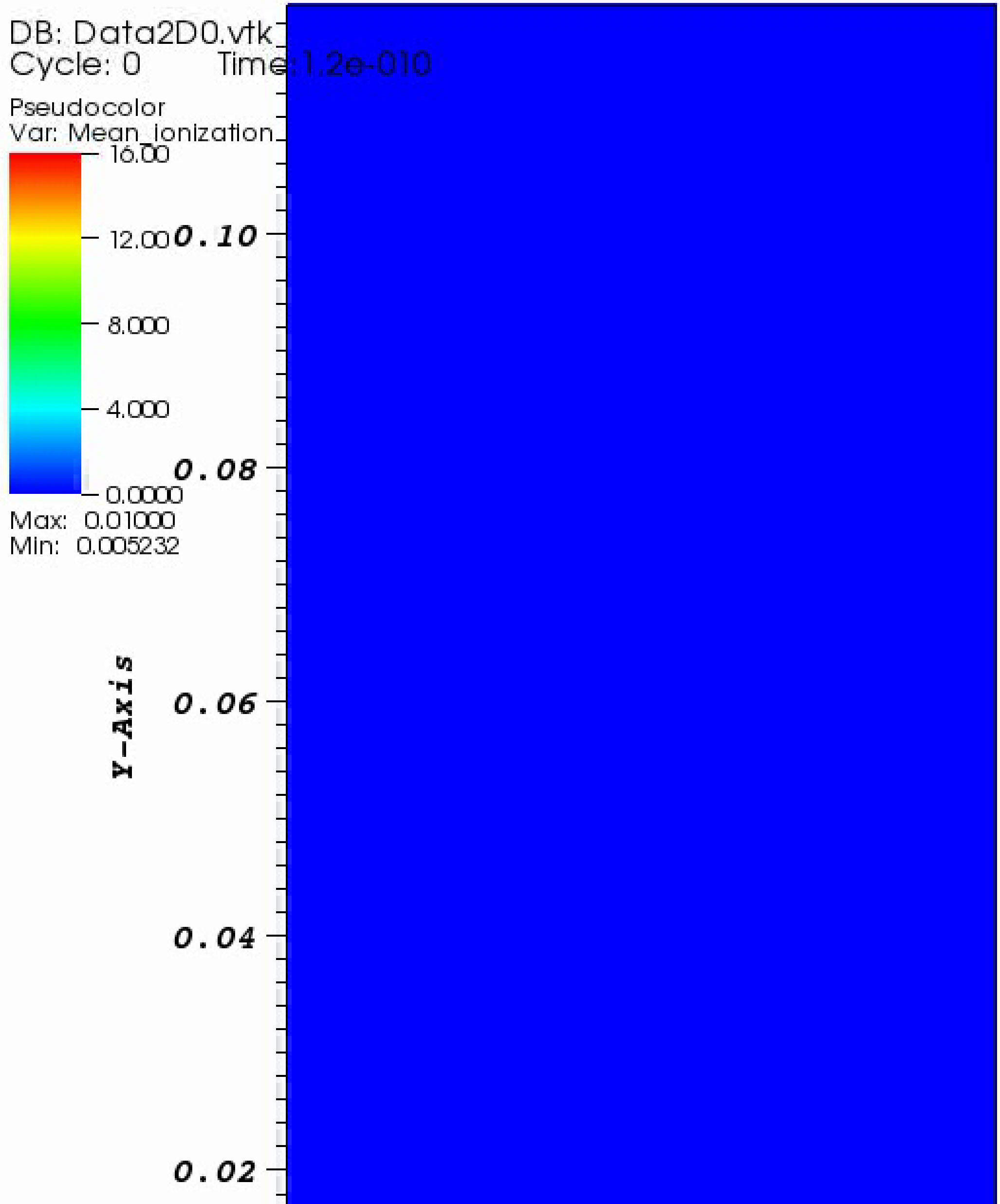


Laser

Initial atomic density

Mean ionization

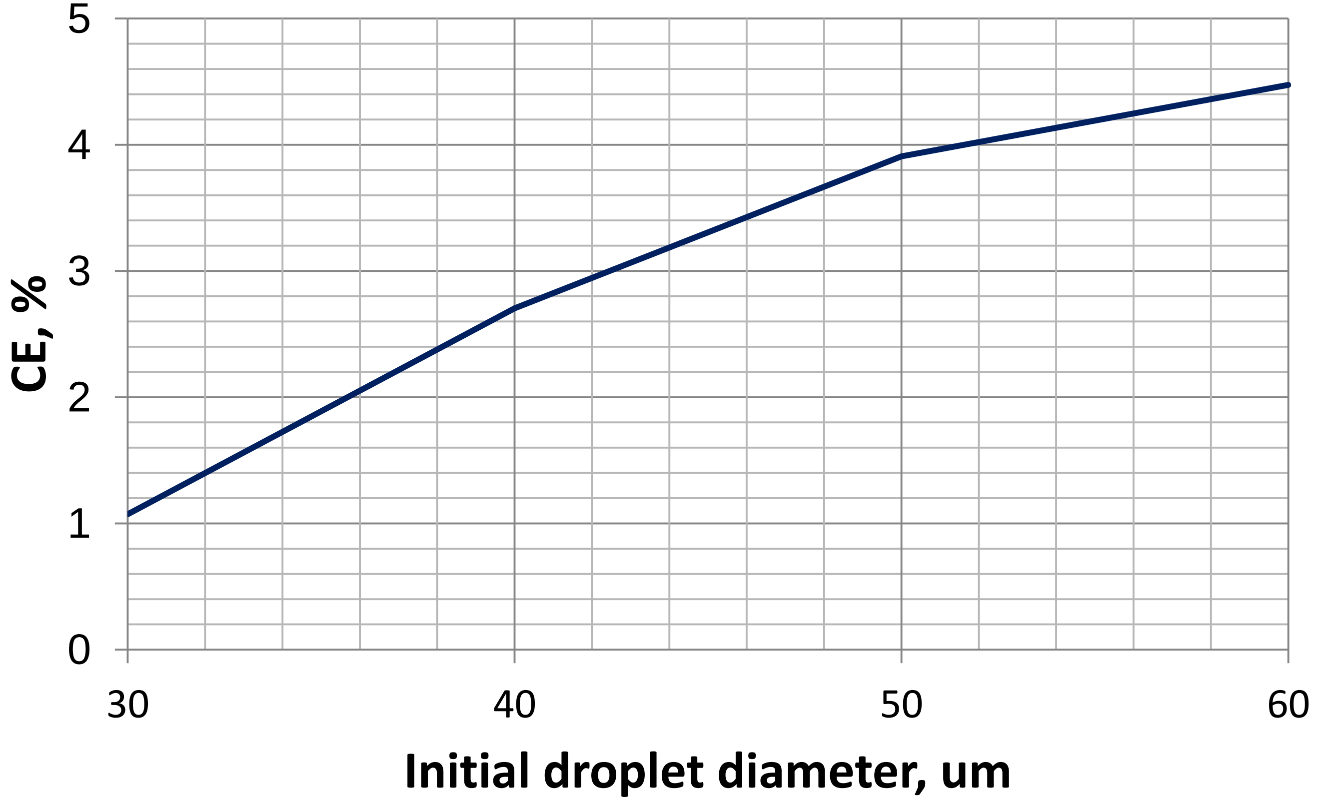




Benefits of distributed target

- Considered on example of this particular geometry, still other geometries may increase some benefits at the expense of some others
- "Ideal geometry" really dependent on EUV source approach, therefore can not be found without taking into account their important features: level of gas pressure gas flow and so on

CE of spherical layer target as a function of initial droplet diameter



Q = 0.5 J
Time = 100 ns
Spot = 200 um(1/e^2)

Diameter of sphere – 300 um
Depth of layer – 30 um
Fragment size – 1 um

Large CE compared to droplet like target is first benefits of distributed target

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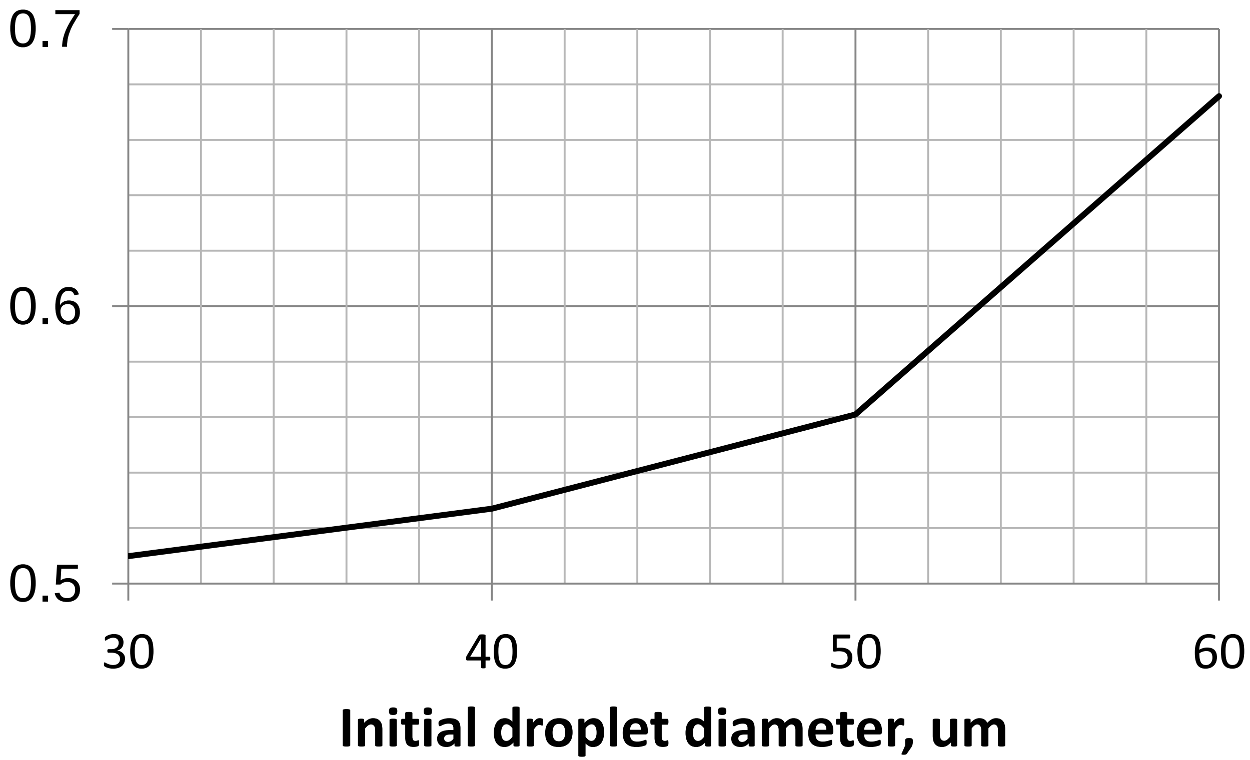
Anisotropy is characterized by the ratio of EUV in band energy in 2π of condenser mirror to that in 4π



Q = 0.5 J
T = 100 ns
Spot = 200 um(1/e^2)

Diameter of sphere – 300 um
Depth of layer – 30 um
Fragment size – 1 um

0.5 – isotropic, 1 – only in 2π of the mirror

Anisotropy of EUV radiation is one of the reason of increased CE (gives about 1.2% of additional CE at 60 um droplet)

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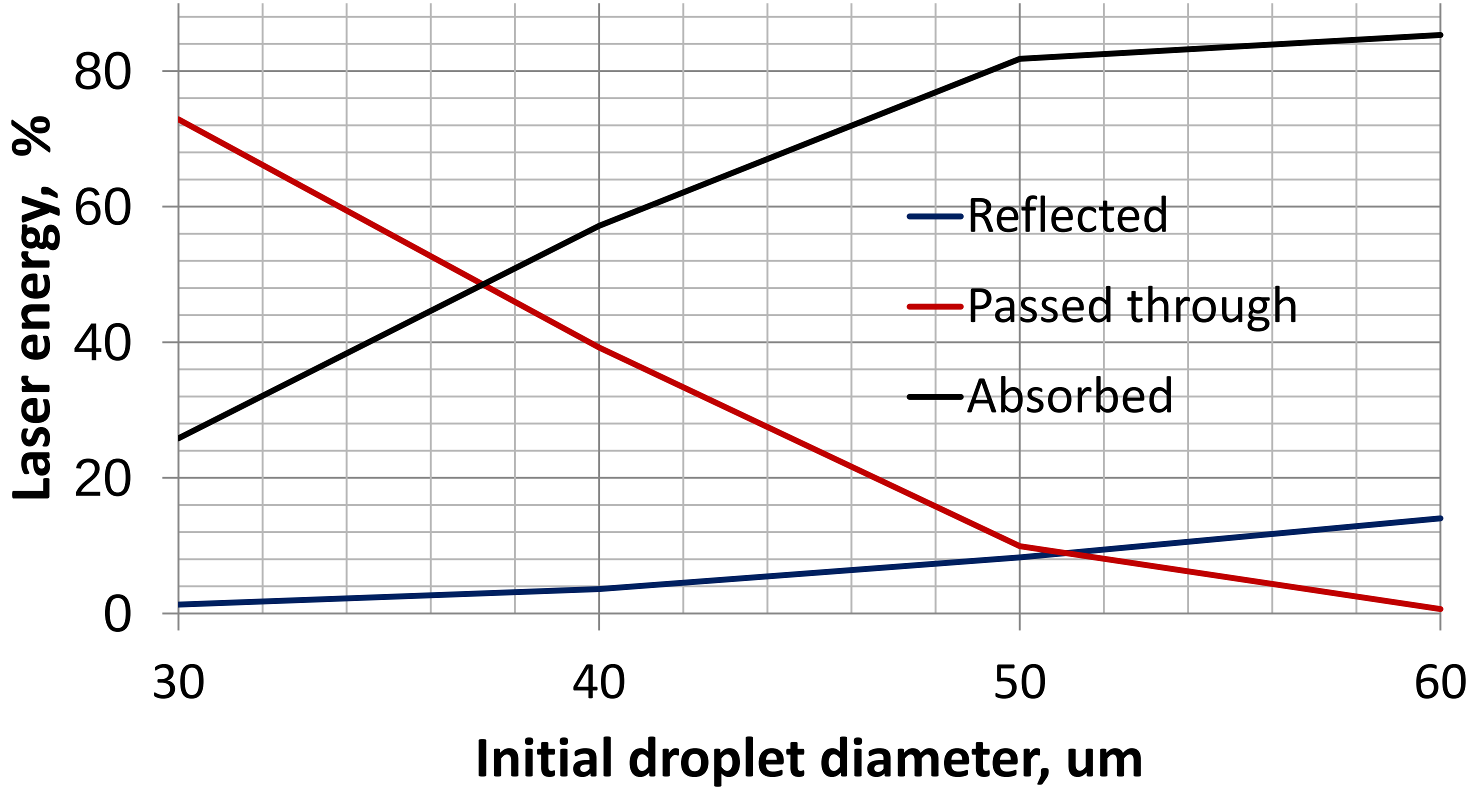
Effectivity of laser energy usage – way leading to high CE of distributed target



Q = 0.5 J
Time = 100 ns
Spot = 200 um (1/e^2)

Diameter of sphere – 300 um
Depth of layer – 30 um
Fragment size – 1 um

Density of plasma increases with droplet size thus decreasing passed through energy and increasing to some extent reflected energy. As a result absorbed in plasma energy is increasing gradually with droplet size.

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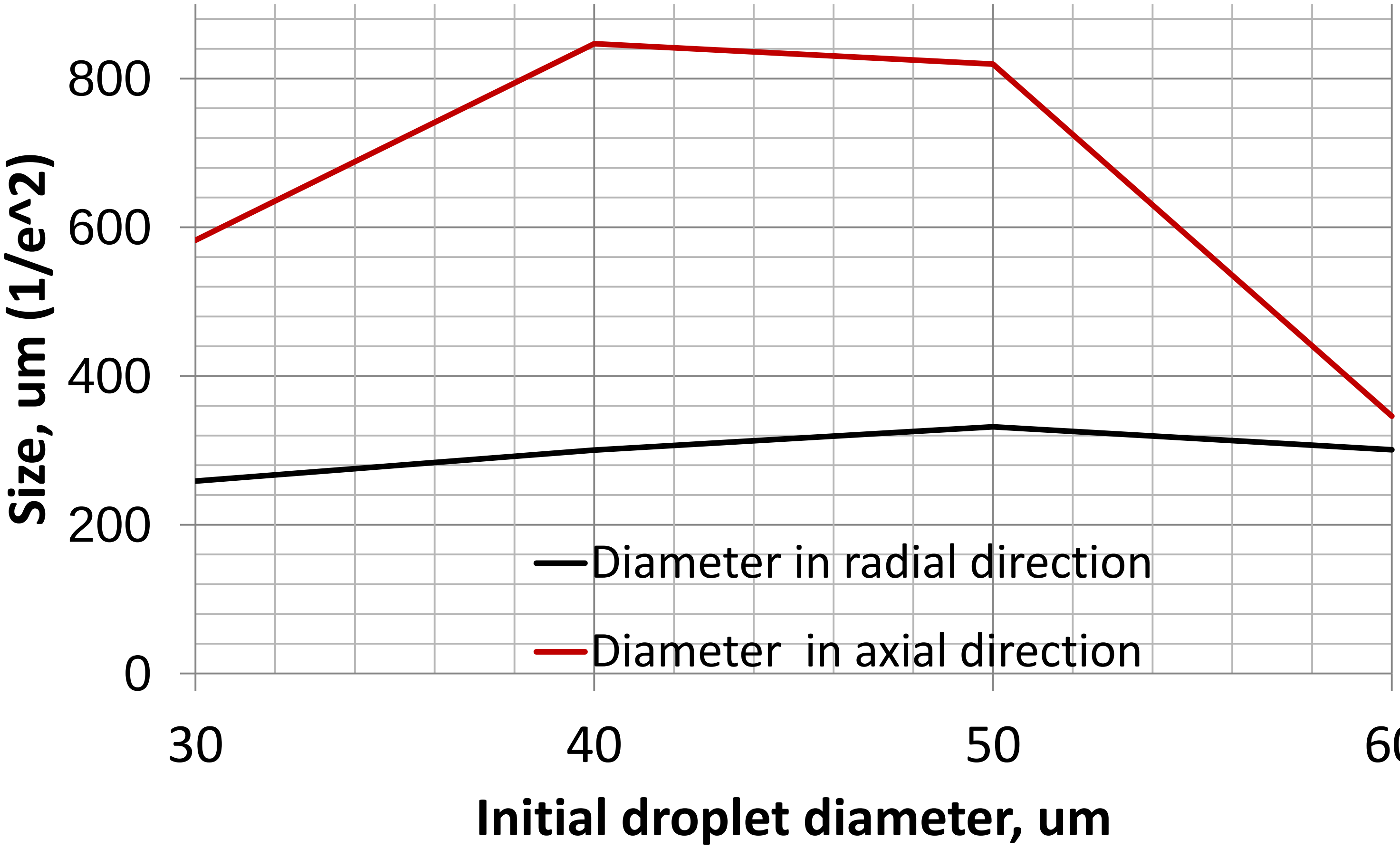
Radial and axial sizes of EUV source



Q = 0.5 J
Time = 100 ns
Spot = 200 um (1/e^2)

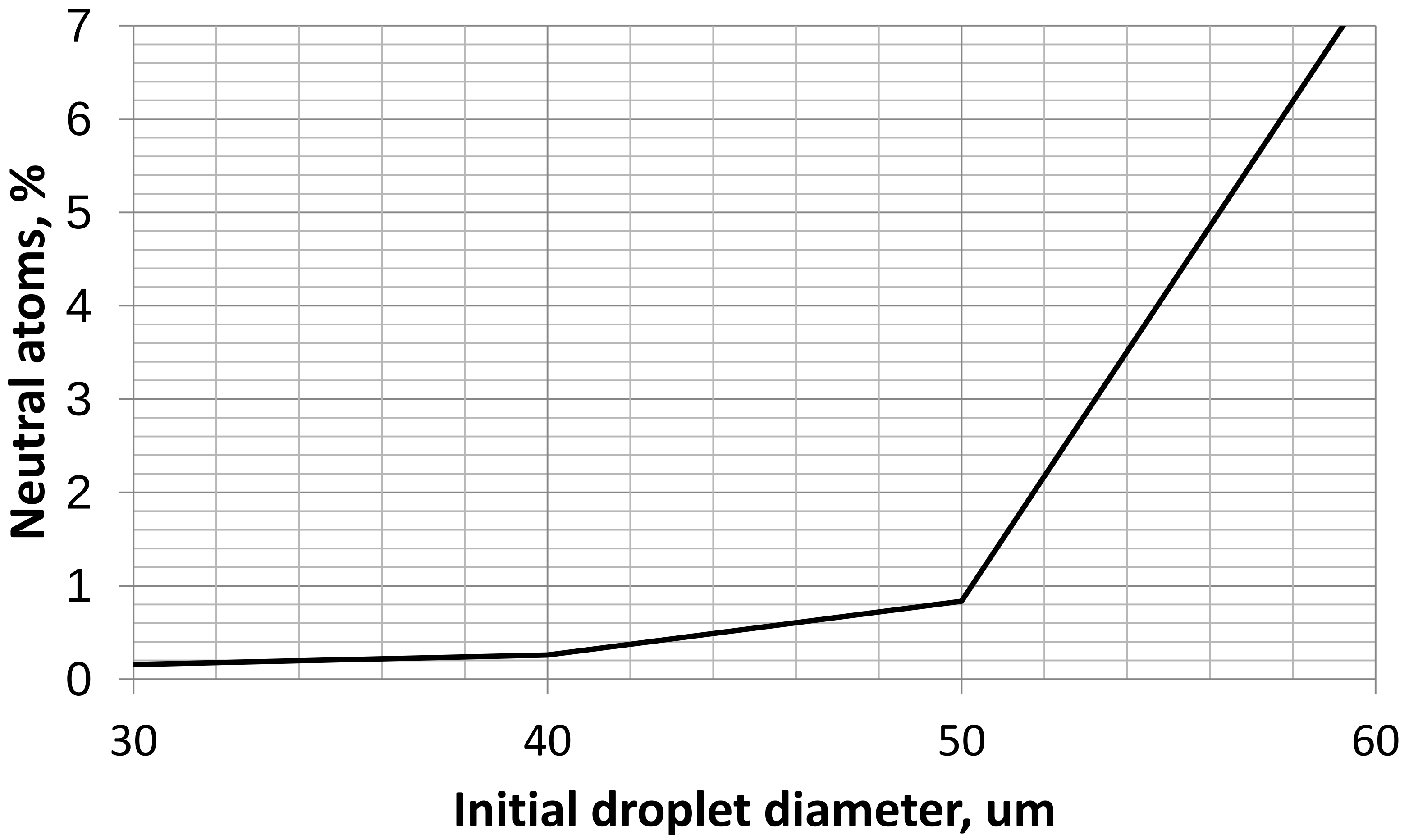
Diameter of sphere – 300 um
Depth of layer – 30 um
Fragment size – 1 um

Droplet size changes mainly axial EUV source size, fragment size is also affect EUV source size (not shown)

Full evaporation of distributed target as a benefit

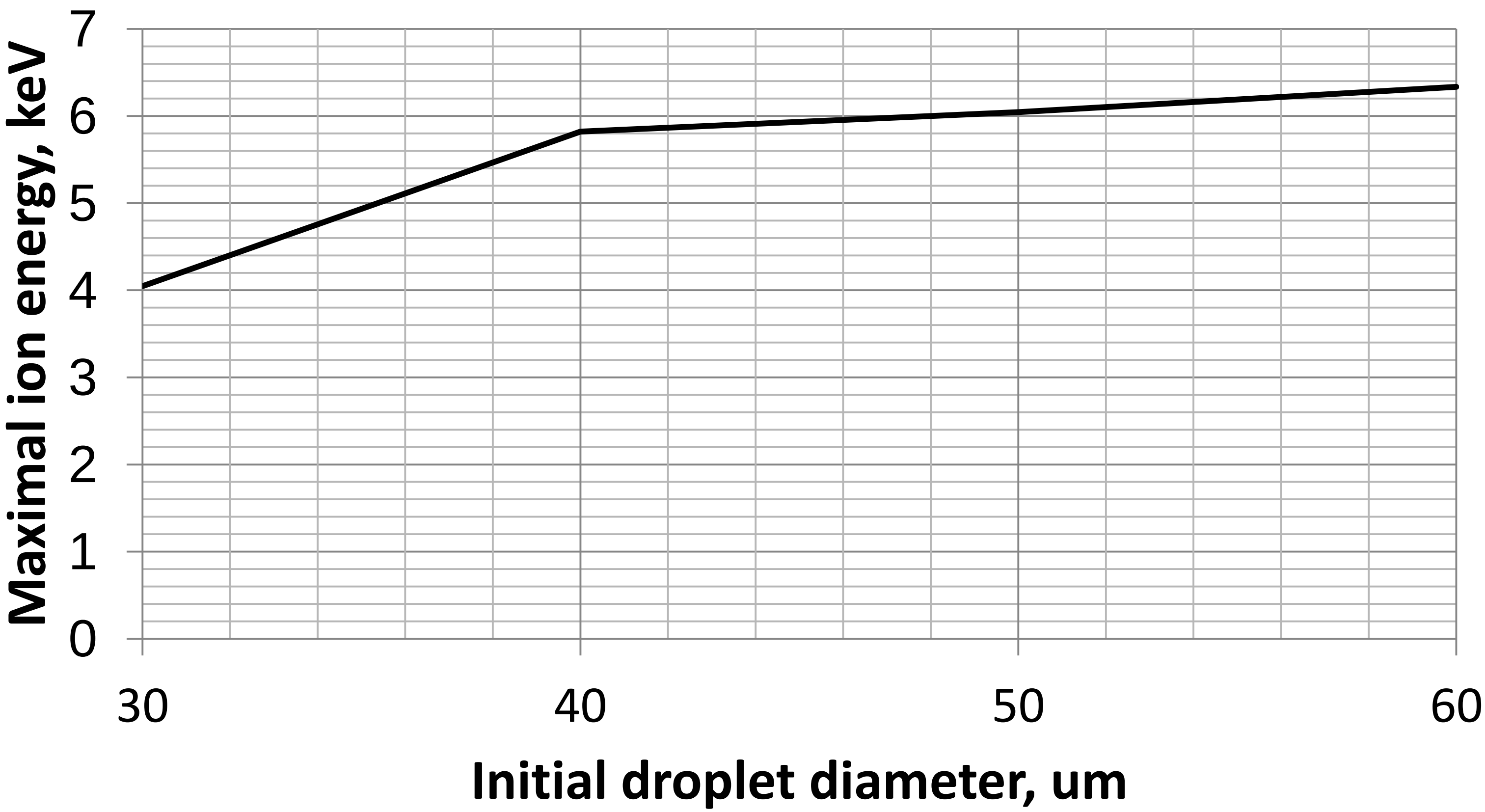
- There is no problem with fast fragments after EUV pulse in distributed target since target may be fully evaporated, as in all cases shown here
- The reason for that is simple: problem with single droplet was with small surface of it. After pre-pulse surface increases greatly thus increasing rate of evaporation.
- Of course it is a function of fragment size and at 3um fragments and 60 um initial droplet target is not evaporating entirely
- Code can give number of non-evaporated fragments as well as their distribution in size, velocity and angles. That can help to understand how dangerous they are (can they be gathered somehow for example)

Number of not ionized atoms to the end of process



At low gas pressure in the EUV source, number of “neutral atoms remains” may be important. As a result trade off between CE and this value is possible

Ion energy



Maximal ion energy looks rather high here. Still number of fast ions and their angle distribution is also important. They are shown on next slide for 60 um droplet

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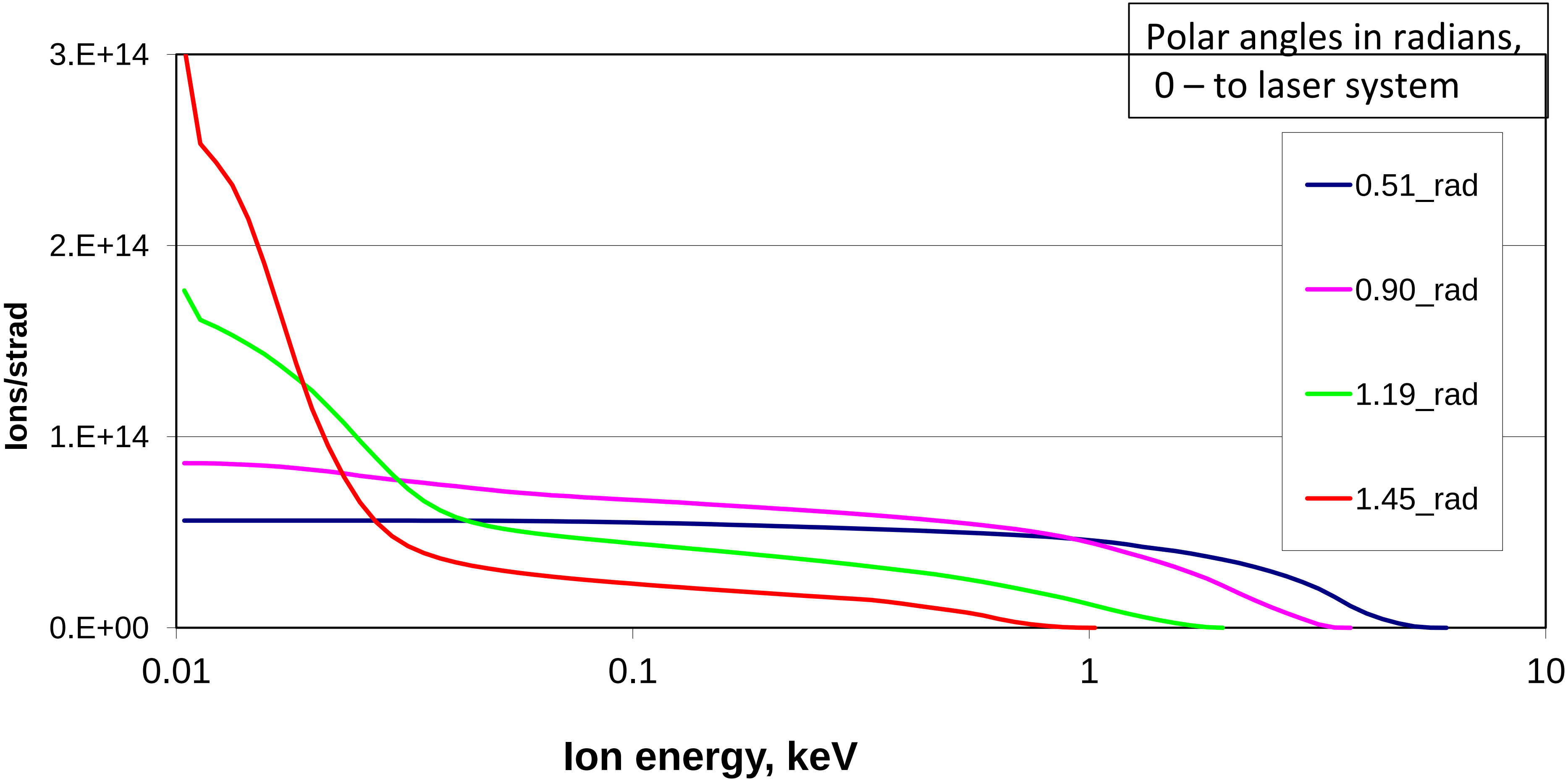
Ion energy distribution function, 60 um droplet



1. Number of fast ions with energy > 3 keV is about 2.e13, only 0.5% of full number of ions.
2. Geometry considered may be not optimal in respect decreasing ion energy

Conclusion

- Distributed target are more perspective for creating EUV source for HVM comparing with droplet-like ones due to
  - more then double CE
  - decreased problem with non-evaporated part of target
  - decreased reflection of CO2
  - decrease number of neutral Sn atoms
- LPP source on distributed target is many-parametric task with many limitations, which means that fast and stable code like RZLINE, can be useful in finding regions of interesting parameters for checking in the experiment

Thank you very much for your attention